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# Neural Correlates of Verb Argument Structure Processing

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# NEURAL CORRELATES OF VERB ARGUMENT STRUCTURE PROCESSING

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## ABSTRACT

Verb argument structure (VAS) is pivotal to sentence production and comprehension, since it determines participant roles, as well as their grammatical form and syntactic position in a sentence. Neural correlates of VAS processing have mainly been studied in terms of the number of arguments. Data on the neural and behavioral effects of other VAS characteristics are limited, whereas they would have implications for behavioral and brain stimulation treatments of language disorders.

The present research investigated behavioral and neural effects of three understudied VAS characteristics (number of subcategorization options, number of thematic options and number of number-of-argument options) in single-word-level and sentence-level processing. The results indicate that their effects are highly dependent on processing conditions. A greater complexity in terms of the number of subcategorization and thematic options facilitated single-word processing, possibly due to making verb representations "stronger" and providing them with a greater number of connections in the mental lexicon, but had a detrimental effect in sentence processing, where VAS information needs to be processed to a fuller extent. VAS processing was associated with activation in bilateral (although mainly left-lateralized) frontal, temporal and parietal brain areas, including consistent activation in the left middle temporal gyrus. The third characteristic, the number of number-of-argument options, did not appear to have a robust neural or behavioral effect.

The present research suggests that VAS effects may have a semantic nature, rather than originate from a dedicated VAS module in verb representations, because they were only found for two VAS characteristics that have semantic correlates and because no evidence of automated exhaustive access to purely grammatical VAS information was found in shallower (single-word) processing conditions. This provides a novel account for VAS effects. Still, regardless of the nature of VAS effects, the present research suggests that the number of subcategorization and thematic options of verbs should be taken into account in selection of stimuli for complexity-based behavioral treatments of aphasia. Another clinical implication of this research is that it suggests potential target sites (mainly, left middle temporal gyrus) for brain stimulation treatments of verb and sentence processing.

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# CHAPTER 1

## INTRODUCTION

Verbs occupy a pivotal role in sentence construction. They determine the number of arguments (participant roles) that should appear in a sentence, their thematic roles (such as agent, i.e. the performer of an action, or object, i.e. someone or something to whom the action is performed) and their linguistic properties, such as their syntactic position in a sentence (subject, direct object, etc.) and possible grammatical class realization (such as noun phrase, prepositional phrase, dependent clause, etc.; options of the verb with regard to possible grammatical realization of arguments are referred to as subcategorization options). The interpretation of the elements of the sentence depends on the argument structure of the verb: for example, a noun phrase '*to Harry*' may be interpreted as having, among others, semantic roles of a recipient or location, depending on the argument structure of the verb that it appears with: cf. *I sent a threatening letter to Harry* vs. *I stapled a threatening letter to Harry* (Boland & Blodgett, 2006).

The pivotal role of verbs in the sentence structure (both in production and comprehension) is the reason why research on verbs is not only important for fundamental theoretical understanding of language representation in the brain, but also has a direct clinical significance. Understanding which characteristics of verbs render their processing more or less difficult may suggest criteria of verb and sentence selection for speech-language therapy programs for individuals with language disorders such as aphasia, whose verb processing deficits may often underlie impairments of sentence production and comprehension.

One fundamental characteristic of verbs is their argument structure (henceforth, VAS). The goal of this dissertation is to investigate neural and behavioral effects of several understudied VAS characteristics on language processing in healthy young speakers. The introduction will outline the notion of verb argument structure in linguistic theory and present the current understanding of its cognitive and neural correlates found in psycho- and neurolinguistic research. The next sections will present data from two neuroimaging and one behavioral experiment.

## 1.1. Theoretical linguistic background

Arguments may be thought of as "elements of meaning that a word needs to express a complete thought" (Traxler, 2011). That is, they correspond to necessary roles of situation participants, which may or may not be necessarily expressed overtly. For example, the verb '*to give*' has three arguments: agent (<u>who</u> is giving), object (<u>what</u> is being given) and a recipient (<u>who</u> is being given something <u>to</u>), which are all necessary "participants" of the situation of giving. VAS information describes "a relationship between events (including states) and event participants and their distribution and realization in sentences" (Marantz, 2013).

Arguments need to be distinguished from adjuncts, which are optional elements of sentence structure that complement the verb meaning rather than constitute its core components. An example of an adjunct would be the noun phrase '*in the woods*' in the sentence *The man hunted a deer in the woods*, where the omission of this noun phrase would not violate the grammaticality of the sentence and / or would not essentially change the meaning of the verb '*to hunt*'.

The argument structure hypothesis within the lexicalist framework suggests that information related to VAS is stored in the lexicon (Boland & Boehm-Jernigan, 1998; Boland and Blodgett, 2006), whereas adjunct attachment relies on general (non-lexical) grammatical mechanisms. Arguments and adjuncts demonstrate numerous differences in their linguistic behavior. In the English language, linguistic criteria allowing to distinguish between them include optionality, relative linear ordering in a sentence, possibilities of '*do so*' substitution, possibility of extraction from syntactic islands, possibility of iteration, possibility of coordination with elements of the same type, movement with the verb in verb phrase pre-posing, etc. (e.g., Ross, 1967; Bresnan, 1982; Huang, 1982; Williams, 1994). Additionally, a large body of psycholinguistic evidence addresses differences in processing of arguments versus adjuncts, which will be discussed in the Section 1.2.

Researchers working within the lexicalist or, as it is often dubbed in theoretical linguistic work (e.g., Rappaport Hovav and Levin 1998), projectionist framework name several parameters that may be considered part of the VAS information. The characteristic that is most commonly included to be part of VAS is the number of arguments, sometimes also referred to as the number of thematic roles (e.g., Thompson & Meltzer-Asscher, 2014; Meltzer-Asscher et al., 2015). For example, verbs may have only one argument (intransitive verbs, e.g., '*laugh*': *Jack laughs*), two arguments (transitive verbs, e.g., '*call*': *Jack calls Anna*), or three arguments (ditransitive verbs, e.g., '*give*': *Jack gives Anna a present*). Then, VAS may also entail the specification of the thematic roles of arguments: e.g., the argument of the intransitive verb '*to fall*' has a thematic role of a patient (i.e., a more "passive" participant that the action is "happening to"), whereas the argument of the intransitive verb '*to run*' has a thematic role of an agent (i.e., an active participant executing the action). Lastly, VAS may also entail morphosyntactic information that postulates how the verb's arguments may be realized in a sentence: namely, what syntactic positions they may appear in and what their possible grammatical realization, or subcategorization options, may be. For example, some transitive verbs may only attach noun phrases as their second argument (*He completed the work / *He completed that…*[1]), whereas others may be complemented both by noun phrases and by dependent clauses (*He forgot the poem / He forgot that he had an appointment*).

It is particularly important to note that a verb may also have multiple possible argument structure options, or frames, that differ on all or some of the above specific VAS characteristics. For example, the verb '*to donate'* may be used in at least two frames (*He donated the clothes; He donated the clothes to the church*) that differ in the number of arguments and, consequently, in their thematic roles and subcategorization frames. In some cases, VAS options of the same verb form may differ to an extent where one may possibly consider there to be several homonym verbs with separate lexical entries (e.g., the VAS characteristics of '*to walk*' in *Johns walks* and *John walks the dog* differ in the number of arguments and their thematic roles, so one may possibly talk about two homonym verbs).

However, even within the lexicalist tradition, not all researchers necessarily consider all of the above characteristics to be integral parts of VAS information in, or in

[1] Here and below, the symbol * is used to denote not-well-formed (unacceptable) linguistic structures.

direct association with, the verb's lexical entry[2]. For example, some may argue that whereas the number and thematic roles of participants are stored as part of the verb's lexical entry, the subcategorization options may simply follow from thematic roles, i.e., information about them can be induced from online processing of linguistic context and does not need to be explicitly stored in the lexicon. Thus, a central question in VAS research is which VAS characteristics exactly are stored in the lexicon and under what conditions they are retrieved.

Moreover, contrary to the lexicalist approach that states that at least some VAS information is linked to or contained in the verb's lexical entry and projected to the sentence, proponents of the constructivist view emphasize the role of syntactic context and do not consider it necessary to postulate that any argument structure information has to be a component of the verb's lexical entry at all (Hale & Keyser, 2002). Proponents of this framework argue that any information that lexicalists consider to be stored as part of VAS (e.g., the number of words that can be associated with the verb, their semantic roles, their possible grammatical realization) is actually only dependent on the verb's meaning and thus there is no reason to postulate an additional VAS component in the verb's lexical entry. Instead, building of structures is restricted only by world knowledge (or knowledge of event structures associated with verbs (Pustejovsky, 1991)) and the perceived VAS information is only a 'read-out' from syntactic structure (Borer, 2005).

[2] Here and below, the term "lexical entry" is used as a traditional way to describe all information about the word that is available to the language user (e.g., Levelt, 1992). However, it is not implied that lexical entries are necessarily enclosed units that are contained in a "dictionary-like" mental lexicon and include full information about the word. Rather, information about any lexical items may be stored in a distributed way by means of connections between elements of lexical knowledge (e.g., Elman, 2011). Thus, by saying that a certain type of information is stored as part of or in association with the verb's lexical entry, what is meant here is that this information is strongly associated with the verb and becomes available to the language user when using the verb, regardless of what architecture is assumed for storage of lexical knowledge.

An intermediate approach is taken by construction grammar. It basically states that the verbs' lexical entries do include VAS information in some form but this information can be used creatively by language speakers in constructions that are not necessarily stored in association with the verb's meaning (Goldberg, 1999). For example, even though the lexical entries of the verbs '*to kiss'* and '*to rumble*' contain some information about what their arguments may be, information about the possibility of constructions such as *He kissed her unconscious* and *The truck rumbled down the street* is not part of the VAS component of the verb's lexical entry. Rather, their meanings are formed as a result of integration of the verb's VAS information and the meaning of the construction itself. Verbs may be divided into numerous classes based on the possibility of their use in specific grammatical constructions: for example, Levin (1993) and Kipper et al. (2008) have suggested more than 200 classes of the English verbs.

To summarize, there is no consensus with regard to the extent of VAS information that is stored as part of or in association with the verbs' lexical entries. Whereas constructivist frameworks deny the necessity of the VAS component at all, lexicalist and to some extent construction grammar frameworks state that at least some VAS information needs to be associated with the verb in the mental lexicon. Besides the common characteristic of the number of arguments, VAS information may also include information about other characteristics such as the arguments' possible thematic roles and subcategorization options, as well as whether the verb has any alternations of all or some of VAS properties. The crucial question is which exactly (if any) of these characteristics are indeed stored as part of lexical knowledge about verbs and under what processing conditions VAS information is retrieved. While this research is conducted in the context of the lexicalist versus constructivist debate in theoretical linguistics, its scope is not to attempt to decide between these two approaches but rather to investigate which VAS characteristics have an effect on verb processing cost under which circumstances.

### 1.2. Psycho- and neurolinguistic research

The notion of VAS originated in theoretical linguistic research but has also received a lot of attention in the fields of psycho- and neurolinguistics. A body of psycholinguistic studies provides support for the theoretical linguistic distinction between arguments and adjuncts. The evidence includes preferential interpretation of noun phrases as verb arguments rather than adjuncts (Abney, 1989), faster reading times for argument than adjunct relations (Liversedge et al., 1998), higher "well-formedness" judgments for sentences including verb arguments compared to adjuncts (Boland & Boehm-Jernigan, 1998), different priming patterns for combinations of verbs with arguments vs. adjuncts (Traxler, 2008), etc.

Based upon this psycholinguistic evidence, it appears that regardless of our view of how VAS information may be stored or reconstructed, the processing of verb arguments differs from processing of adjuncts in many respects. Further support comes from neurolinguistic studies seeking to find the neural correlates of VAS processing. For instance, electrophysiological evidence suggests that healthy speakers show online sensitivity to violations of VAS, such as verbs being used with a greater or smaller number of arguments than required by their VAS properties (Friederici et al., 2004; Frisch et al., 2004).

In addition to generally showing that arguments are processed differently from adjuncts, a body of psycho- and neurolinguistic research has investigated specific VAS characteristics. Current findings for individual VAS characteristics are summarized below.

### *1.2.1. Number of arguments*

So far, the most extensively studied VAS characteristic has been the number of arguments[3] (or, in other terminology, participant roles). Generally, verbs with a larger number of arguments have been shown to impose a greater processing cost (with some exceptions: e.g., Thompson et al., 2007), which is reflected, for example, by slower reaction times in various tasks. So far, the behavioral effect has mainly demonstrated in single-word-level tasks, such as naming (Malyutina & den Ouden, unpublished), lexical decision (Rodriguez-Ferreiro, Andreu, & Sanz-Torrent, 2014) or word class judgment (Rodriguez-Ferreiro, Andreu, & Sanz-Torrent, 2014); however, some of the evidence comes from sentence processing (e. g., cross-modal lexical decision interference paradigm (Shapiro et al., 1991; Ahrens & Swinney, 1995)). It is noteworthy that all studies showing facilitatory or null effects of a greater number of arguments, rather than a more commonly found detrimental effect, employed a lexical decision task (although see a detrimental effect of a greater number of arguments found in a lexical decision experiment by Rodriguez-Ferreiro, Andreu, & Sanz-Torrent, 2014 – this study differed from other lexical decision experiments in that it was conducted in Spanish rather than English and used extremely short (500 ms) stimulus presentation, although it is still unclear how this may have contributed to conflicting results). It may be possible that the lexical decision task, which involves shallow single-word processing, may draw on VAS

[3] The number of arguments has traditionally been defined as a measure of whether a subject, a direct object and an indirect object are present in VAS. Verb's associates of a more questionable status (such as obligatory prepositional phrases, e.g., the second argument of the verb '*to consist*': *This book consists of two chapters* vs. **This books consists*) have not been included in research on the number of arguments yet.

access in a different way than tasks inducing deeper processing, and not require access to all VAS components. Thus, research is warranted that would systematically investigate how VAS effects are modulated by processing conditions by using the same experimental design and, where possible, the same stimuli across multiple tasks. Previous behavioral evidence on the effects of the number of arguments (coming from behavioral studies and neuroimaging studies that report behavioral results) is summarized in Table 1.1.

*Table 1.1*. Previous findings on the behavioral effect of the number of arguments.

| *Effect of greater number of arguments* | *Work* | *Task* | *Specific behavioral effects* |
|---|---|---|---|
| Detrimental | Shapiro et al., 1991 | Cross-modal lexical decision interference paradigm | Verbs with four complements integrated into sentence slower than transitive verbs |
| | Ahrens & Swinney, 1995 | Cross-modal lexical decision interference paradigm | Ditransitive verbs integrated into sentence slower than transitive verbs |
| | Rodriguez-Ferreiro, Andreu, & Sanz-Torrent, 2014 | Lexical decision | Transitive verbs slower than intransitive verbs |
| | Rodriguez-Ferreiro, Andreu, & Sanz-Torrent, 2014 | Word class judgment | Transitive verbs slower than intransitive verbs |
| | Malyutina & den Ouden, unpublished | Naming | Transitive verbs slower than intransitive verbs |
| Facilitatory | Thompson et al., 2007 | Lexical decision | Intransitive verbs slower than transitive and ditransitive verbs |
| Null results | Thompson et al., 2010 | Lexical decision | N/s (ditransitive vs. transitive vs. intransitive verbs) |
| | Malyutina & den Ouden, unpublished | Lexical decision | N/s (transitive vs. intransitive verbs) |

n/s – no significant effects

Neuroimaging studies have also found neural differences between processing verbs with a smaller vs. greater number of arguments. Verbs with more arguments have been repeatedly shown to be associated with a higher activation level in a network of left temporal and parietal regions, such as the posterior temporal gyrus, angular gyrus (BA 39) and the supramarginal gyrus (BA 40) (Thompson et al. 2007; Den Ouden et al., 2009; Thompson et al., 2010; Meltzer-Asscher, Mack, Barbieri & Thompson, 2015), rather than exclusively with areas traditionally associated with syntactic processing, such as Broca's area. Just as in the psycholinguistic studies, previous neuroimaging research has largely relied on single-word rather than sentence-level tasks. Thus far, the body of literature is not extensive enough to detect any patterns in whether the effect of the number of arguments appears to be modulated by the task, as in previous behavioral literature. Findings of previous neuroimaging research on the number of arguments are summarized in Table 1.2.

Overall, the findings of both neuroimaging and behavioral research appear to provide evidence of the number of arguments being stored as part of the verb's lexical entry: the cost of processing verbs associated with a greater number of arguments is increased even under conditions when there is no sentence context requiring to process all of the arguments. An overall review of previous behavioral findings in light of experimental tasks suggests that the effect of the number of arguments may possibly be modulated by processing conditions.

*Table 1.2*. Previous findings on the neural correlates of the number of arguments.

| *Work* | *Task* | *Contrast* | *Area of activation* |
|---|---|---|---|
| Ben-Shachar et al., 2003 | Sentence grammaticality judgment | 3-arg > 2-arg | L posterior superior temporal sulcus [ROI] |
| Thompson et al., 2007 | Lexical decision | 2-arg > 1-arg | L angular gyrus<br>L supramarginal gyrus |
| | | 2-arg & 3-arg > 1-arg | L angular gyrus<br>L supramarginal gyrus<br>R angular gyrus[uncorr]<br>R supramarginal gyrus[uncorr] |
| Shetreet et al., 2007 | Semantic judgment of sentences | Parametric analysis (1-arg, 2-arg, 3-arg) | R anterior cingulate gyrus<br>R precuneus |
| Den Ouden et al., 2009 | Action naming (pictures & videos) | 2-arg > 1-arg | Extensive network of L and R parietal, temporal and frontal areas |
| Thompson et al., 2010 | Lexical decision | 2-arg > 1-arg<br>3-arg > 2-arg<br>3-arg > 1-arg | n/s<br>n/s<br>L angular gyrus |
| Meltzer-Asscher et al., 2015 | Lexical decision | 2-arg > 1-arg | L posterior middle temporal gyrus<br>L middle occipital gyrus |

L – left, R - right; n/s – no significant activations; [uncorr] indicates reported activations that are not significant after correction for multiple comparisons, [ROI] indicates reported activations from ROI analyses. No activation was found in any contrasts in the opposite direction to those listed in the table.

### *1.2.2. Subcategorization options*

Another VAS characteristic that has been addressed by a limited body of research is the number of the verb's subcategorization options, i.e., possible grammatical class realizations of the verb's arguments. Early work by Fodor, Garrett and Bever (1968) demonstrated that verbs that allow more subcategorization options (noun phrases and subordinate clauses) are more difficult to process in paraphrasing and anagram solution tasks than verbs that only allow noun phrases, even when placed in the same type of sentence structure (i.e., noun phrase contexts). The effect was replicated for the two verb types inserted into the same type of context in the rapid visual presentation comprehension task (Holmes & Forster, 1972) and time-compressed speech comprehension task (Chodorow, 1979). However, conflicting evidence comes from work by Shapiro and colleagues. Shapiro, Zurif & Grimshaw (1987) conducted an experiment where subjects performed a complex secondary task during sentence processing and found that an increased number of subcategorization options did not render verb processing more difficult. The authors argue that the effect of subcategorization options found in earlier works could be due to tasks effects and not be representative of online language processing under normal conditions. Rodriguez-Ferreiro et al. (2014) did not find a behavioral effect of subcategorization options either, using a lexical decision and a word-class judgment task. Previous behavioral evidence on the effects of the number of subcategorization options (coming from behavioral studies and neuroimaging studies that report behavioral results) is summarized in Table 1.3.

In line with earlier works, rather than evidence from Shapiro et al. (1987) and Rodriguez-Ferreiro et al. (2014), a recent neuroimaging study by Shetreet et al. (2007) found that processing verbs (in Hebrew) with a larger number of subcategorization options was associated with increased activation in the left superior temporal gyrus and pars orbitalis of the left inferior frontal gyrus (Brodmann's area 47). As suggested by Thompson and colleagues (2010), these findings are consistent with Humphries, Binder, Medler, and Liebenthal (2006) who argued that frontal regions may be crucial for "extracting syntactic structure independent of sentential meaning". Similarly, Shetreet et al. (2010) found that processing the number of subcategorization options was associated with the left superior temporal gyrus. Findings of neuroimaging research of the number of subcategorization options are summarized in Table 1.4.

*Table 1.3*. Previous findings on the behavioral effect of the number of subcategorization options.

| *Work* | *Task* | *Behavioral effects* |
|---|---|---|
| Fodor, Garrett and Bever, 1968 | Paraphrasing; anagram solution | Sentences containing verbs with more subcategorization options processed slower |
| Holmes & Forster, 1972 | Rapid visual presentation comprehension task | More challenging processing (fewer words remembered) from sentences containing verbs with more subcategorization options |
| Chodorow, 1979 | Time-compressed speech comprehension task | Lower comprehension of verbs with more subcategorization options |
| Shapiro, Zurif & Grimshaw, 1987 | Cross-modal lexical decision interference paradigm | N/s |
| Rodriguez-Ferreiro et al., 2014 | Lexical decision | N/s |
| Rodriguez-Ferreiro et al., 2014 | Word-class judgment | N/s |

n/s – no significant effects

*Table 1.4*. Previous findings on the neural correlates of the number of subcategorization options.

| *Work* | *Task* | *Contrast* | *Area of activation* |
|---|---|---|---|
| Shetreet et al., 2007 | Semantic judgment of sentences | Parametric design (verbs with 1, 2, 3 options) | L superior temporal gyrus<br>L inferior frontal gyrus (BA 9, 47) |
| Shetreet et al., 2010 | Semantic judgment of sentences | 2 options > 1 option | L superior temporal gyrus |

L – left, R - right; n/s – no significant activations. No activation was found in any contrasts in the opposite direction to those listed in the table.

### *1.2.3. Thematic roles*

Another characteristic of VAS complexity that has received some attention in previous research are thematic roles of the verb's arguments. An fMRI study by Meltzer-Asscher et al. (2013) has addressed thematic roles of verbs' arguments by contrasting, on the one hand, alternating transitivity verbs (e.g., '*to break*', '*to boil*') that can appear in both transitive frames (such as *The boy broke the glass*) and intransitive frames where the only argument has a thematic role of a patient (such as *The glass broke*) and, on the other hand, non-alternating unergative verbs (e. g., '*to run*') that can only appear in intransitive frames where the only argument has a thematic role of an agent (such as *The boy runs*). Alternating verbs may be considered to have a greater thematic role complexity[4] because, first, they have two options with regard to what number-of-argument frames they can appear in and, second, because their subject has a thematic role of a patient in the one-argument frame. The thematic role of a patient is less common or "canonical" for the subject position than the thematic role of an agent and possibly involves syntactic movement of the patient from its original object position, where it is generated as the complement of the verb at the underlying level, to the subject (specifier) position in the syntactic structure (Levin & Rappaport-Hovav, 1994). Meltzer-Asscher and colleagues found that the processing of more complex alternating verbs was associated with increased activation of bilateral angular and supramarginal gyri, middle and superior temporal and middle and superior frontal gyri. However, their experimental design was not able to tease apart whether the effect was due to greater complexity of alternating

[4] Here and below, the terms 'complexity' and 'complex' refer to theoretical linguistic characteristics of verbs rather than to the actual processing load experienced by language users. E.g., verbs with a greater number of thematic options are called "complex" because their representations presumably entail a greater amount of linguistic information compared to verbs with one thematic option, regardless of whether this "complexity" actually makes verb processing easier or more difficult for the speaker.

verbs with regard to the number of number-of-argument frames that they can be used with vs. with regard to allowing a more complex thematic role (a patient) of the subject.

Along the same lines, Meltzer-Asscher et al. (2015) contrasted more complex unaccusative verbs to transitive and unergative verbs and found that thematic role complexity (or, in their terms, non-canonicity) was associated with greater activity in the left precentral and inferior frontal gyri. However, in this case as well, the experimental design still has the caveat of not being able to distinguish between whether the effect is due to greater complexity of alternating verbs with regard to the number of number-of-argument frames that they can be used with vs. with regard to allowing a more complex thematic role (a patient) of the subject. All previous neuroimaging findings on thematic roles are summarized in Table 1.5. (The summary of previous behavioral findings is not given because, to the best of our knowledge, no studies have investigated the effect of the number of thematic options independently of other factors.)

*Table 1.5*. Previous findings on the neural correlates of thematic role complexity.

| *Work* | *Task* | *Contrast* | *Area of activation* |
|---|---|---|---|
| Meltzer-Asscher et al., 2012 | Lexical decision | Alternating transitivity > Unergative | L and R parietal, posterior temporal and middle and superior frontal regions |
| Meltzer-Asscher et al., 2015 | Lexical decision | Unaccusative > Transitive + unergative | L precentral gyrus<br>L inferior frontal gyrus |

L – left, R - right; n/s – no significant activations. No activation was found in any contrasts in the opposite direction to those listed in the table.

*1.2.4. Number of number-of-argument options*

Most studies that have investigated specific VAS properties have assigned their stimuli one value on each of the properties. However, as mentioned in Section 1.1, it is very important that verbs may have multiple argument frame options (alternations) that differ on all or some of VAS properties. Early work by Shapiro (1987, 1989) suggests that the number of number-of-argument options of the verb may actually be the most influential characteristic affecting VAS processing, rather than any specific VAS properties of individual argument frames. Shapiro et al. (1987, 1989) found an effect of the number of different number-of-argument possibilities when participants were confronted with a complex secondary task. Effects were present even when not directly triggered by context, suggesting that access to the structural possibilities of the verb is always exhaustive and all possible argument structures are always activated when language users encounter the verb. An experiment by Ahrens & Swinney (1995), however, used the same paradigm (cross-modal lexical decision interference task) and failed to find an effect of the number of number-of-argument options. Previous behavioral evidence on the effects of the number of subcategorization options (coming neuroimaging studies that report behavioral results) is summarized in Table 1.6.

*Table 1.6.* Previous findings on the behavioral effect of the number of number-of-argument options.

| *Work* | *Task* | *Behavioral effects* |
|---|---|---|
| Shapiro, 1987 | Cross-modal lexical decision interference task | Verbs with a greater number of number-of-argument options integrated into sentence slower |
| Shapiro et al., 1989 | Cross-modal lexical decision interference task | Verbs with a greater number of number-of-argument options integrated into sentence slower |
| Ahrens & Swinney, 1995 | Cross-modal lexical decision interference task | N/s |

n/s – no significant effects

As mentioned in the above discussion of research of thematic roles, results of experiments by Meltzer-Asscher et al. (2012, 2015) may actually also be mediated by the number of number-of-argument frames that a verb can appear in (or, in their terminology, “number of thematic options”), rather than by the contribution of the type of thematic roles per se. Thus, it is increasingly recognized that it is important to carefully isolate dimensions of VAS to avoid confounding by other dimensions, rather than ignore multiple VAS options by characterizing the verb in just one of its possible uses: “it seems rather that alternations are *the* core fact that we need to be able to deal with” (Ramchand, 2014; see also Shetreet, 2014). Several studies have already been conducted that purposefully manipulated the number of number-of-argument frames to investigate specific neural correlates of this parameter. Shetreet et al. (2007) investigated the effect of number of number-of-argument frames (or “thematic frames” in their terminology) by doing a parametric analysis of verbs that have one, two or three frames and found that an increase in the number of options was associated with activation in the left superior temporal and inferior frontal gyri. Shetreet et al. (2010) contrasted “optional” verbs (e.g., *to eat*) to verbs that have multiple subcategorization options but only one number-of-argument frame (e.g., *to discover*) and found that results differed depending on the syntactic context. When optional verbs were presented with a complement, processing of the number of number-of-argument frames was associated with left superior temporal, middle temporal and middle frontal gyri, whereas when optional verbs were presented without a complement, processing of the number of number-of-argument frames was associated with a greater bilateral network of frontal and parietal areas. Meltzer-Asscher et al. (2015) contrasted alternating verbs (i.e., verbs that have several options with regard to what number-of-argument frames they can appear in) vs. non-alternating verbs (i.e., verbs that can appear only in a one-argument or only in a two-argument frame) and did not find any areas of significantly greater activation for either of the two groups. Thus, it appears that the number of number-of-argument frames does not elicit a robust effect at either the behavioral or the neural level, contrary to early findings by Shapiro and colleagues (1987, 1989)[5]. But importantly, the difference of results depending on the context of verb presentation in Shetreet et al. (2010) indicates that VAS may not be accessed uniformly across linguistic contexts (e.g., not all subcategorization options may need to be accessed when one of them is selected by an overt complement). Findings of previous neuroimaging research on the number of number-of-argument frames are summarized in Table 1.7.

*Table 1.7.* Previous findings on the neural correlates of the number of number-of-argument options.

| *Work* | *Task* | *Contrast* | *Area of activation* |
|---|---|---|---|
| Shetreet et al., 2007 | Semantic judgment of sentences | Parametric analysis (verbs with 1, 2 and 3 options) | L superior temporal gyrus<br>L inferior frontal gyrus (BA 9, 47) |
| Shetreet et al., 2010 | Semantic judgment of sentences | Verbs with two SO's > "optional" verbs (presented with a complement) | L superior temporal gyrus<br>L middle temporal gyrus<br>L middle frontal gyrus |
| | | Verbs with two SO's > "optional" verbs (presented without a complement) | L, R frontal and temporal areas |
| Meltzer-Asscher et al., 2015 | Lexical decision | Alternating > Non-alternating 1-arg & 2-arg | n/s |

L – left, R - right; SO – subcategorization options; n/s – no significant activations. No activation was found in any contrasts in the opposite direction to those listed in the table.

[5] Though necessarily speculative, it cannot be ruled out that this pattern (a large effect observed in early studies followed by lack of effect in later studies) is an example of a general "decline effect", i.e., the observation that some scientific claims tend to receive decreasing support over time, possibly due to publication and reporting bias and/or the statistical regression-to-the-mean phenomenon (Ioannidis, 2005).

*1.2.5. Summary*

To summarize, psycho- and neurolinguistic research provides support to the theoretical linguistic notion of VAS, showing that verb arguments are processed differently than adjuncts. Since there is evidence that verbs with different VAS characteristics are processed differently even in equal contexts and processing conditions, psycho- and neurolinguistic evidence suggests that at least some VAS information is automatically exhaustively accessed even when not directly triggered by context. This evidence can be compatible with the lexicalist and construction grammar approaches, both of which posit that at least some VAS information is stored as part of lexical knowledge about the verb. However, the available data can alternatively be accounted for in terms of a less stringent constructivist framework: it is possible that the differences in the processing of verbs with different VAS characteristics may be accounted for by differences in our 'real-world knowledge', i.e., in semantics of the verbs. But ultimately, the important fact is that VAS characteristics have neural and behavioral effects on verb processing, and the nature of these effects poses a separate fundamental research question. Even if VAS effects are ultimately proved to be of a semantic nature (in line with the constructivist framework) rather than be stored in a separate grammatical component of the verb's lexical entry, this does not imply that quantifying verb complexity in terms of VAS characteristics should be abandoned. VAS characteristics could still remain a useful vehicle to quantify the underlying semantic properties of verbs, otherwise hardly measurable. In other words, the scope of the present research is not to attempt to decide between lexicalist and constructivist approaches but rather to investigate which VAS characteristics have effects on verb processing cost, and under what circumstances.

So far, the most well-studied VAS characteristic has been the number of arguments, although the limitations of this research are that mainly single-word-level tasks have been used and also that only subjects, direct objects and indirect objects have been included into this measure, while other “candidates” to arguments, such as obligatory prepositional phrases, have not been investigated yet. However, it has been increasingly recognized (see, e.g., Kemmerer, 2014) that research on more fine-grained word classes and properties may have a greater potential than research on broader categories such as, for example, verbs and nouns or, in this case, pretty crude categories of intransitive, transitive, and ditransitive verbs. An emerging body of research suggests that there may exist distinctive processing patterns and neural correlates of other VAS characteristics besides the number of arguments: e.g., subcategorization options and thematic roles. Another important VAS characteristic is the overall number of the verb’s argument frames; however, evidence of its effects at either the neural or behavioral level is still inconclusive.

In terms of brain correlates, more “complex” VAS has been most consistently shown to be associated with increased activation in left angular and supramarginal gyri, as well as in posterior temporal and inferior frontal regions. Attempts have been made to speculate about the specific roles of these regions in VAS processing: generally, the inferior frontal regions are considered to be involved in “ordering” or structure building, whereas temporo-parietal regions are associated with VAS information storage or retrieval (Meyer et al., 2012; Thompson & Meltzer-Asscher, 2014). However, more research is warranted to investigate which VAS characteristics pose greater "ordering"/integration vs. storage /retrieval demands and under what conditions.

### 1.3. Potential clinical significance for aphasia

Theoretical research of VAS can not only broaden our fundamental theoretical understanding of language representation in the brain, but also have more direct clinical implications for language therapy of language disorders such as aphasia (language impairment caused by focal brain damage such as stroke). One of the characteristics of agrammatic aphasia is the speaker's production of structures that violate VAS requirements. Examples of VAS violations include omitting necessary arguments, adding arguments that the verb does not have or using arguments in an inappropriate syntactic position or in an inappropriate grammatical realization. It appears, therefore, that grammaticality of language production of individuals with agrammatic aphasia should benefit considerably from a treatment focusing on VAS processing (some examples are discussed below in this section).

Current evidence suggests that performance of individuals with aphasia on various verb processing tasks is lower overall than that of healthy speakers but shows similar patterns of sensitivity to VAS characteristics (see below). This suggests that the underlying reason for VAS processing deficits in aphasia may be impaired access to VAS information, whereas the VAS representations themselves are intact at least to some extent and are not qualitatively different from those of healthy speakers (if representations of VAS information were damaged, then specific VAS characteristics would not be able to affect processing in any way).

Again, the most well-studied VAS characteristic has been the number of arguments. Individuals with aphasia have been shown to be more challenged by processing verbs with a greater number of arguments compared to verbs with a smaller number of arguments across different tasks, for example, naming (Kim & Thompson, 2000; Collina et al., 2001), sentence production (Thompson et al., 1997) and narrative production (Thompson, 2003). Other VAS characteristics may also have an impact on the performance of individuals with aphasia. For example, their performance is affected by thematic properties of VAS: it is more challenging for individuals with aphasia to process unaccusative than unergative verbs (Thompson, 2003; McAllister et al., 2009).

The effects of VAS characteristics other than the number of arguments have not been studied extensively in aphasia yet. To the best of our knowledge, no studies have been published on the impact of the number of subcategorization options or number-of-argument frames on verb processing in aphasia. In pilot work in our lab, we have investigated the effect of subcategorization options on verb choice in spontaneous speech by individuals with aphasia (Malyutina, Richardson, & den Ouden, 2014). Samples of spontaneous speech (Cinderella narratives) of 159 healthy control participants and 173 individuals with aphasia (of anomic, Broca's, Wernicke's and conduction type) were obtained from the Aphasia Bank database (MacWhinney et al., 2011) and analyzed for the mean number of subcategorization options in verb used by speakers. When accounting for other linguistic variables such as length and lexical frequency, the analysis did not reveal any differences between participants with aphasia and healthy speakers with regard to the average subcategorization complexity of the verbs used in narratives. This suggests that the effect of not only the number of arguments but also the number of subcategorization options may be the same in aphasia as in healthy speakers. However, more research on the qualitative use of these different verb types is needed, as well as research that uses confrontation tasks, rather than analyze lexical choices in spontaneous speech, to test this hypothesis.

The reason why it is important to know how VAS characteristics affect verb processing in aphasia is that this knowledge could have implications for treatment of agrammatism. Several agrammatism treatment approaches sequence treatment materials according to VAS characteristics of treated items. For example, Bazzini et al. (2012) developed a treatment that is an extension of Mapping Therapy approaches (Rochon et al., 2005) and trains the ability to map VAS information onto syntactic structures. This has proved to be effective for both speed and accuracy of sentence production in agrammatic aphasia. The treated sentences are sequenced in the order of increasing VAS complexity. Thompson et al., (2013), by contrast, have used the general framework of the Complexity Account of Treatment Efficacy (CATE) and thus sequenced the items from more to less complex. They trained participants on producing three-argument verbs in sentence contexts, which led to a positive effect with generalization to verbs with less complex VAS (i.e. one-argument and two-argument verbs). However, none of the treatments so far have attempted to incorporate other measures of VAS complexity besides the number of arguments to characterize the treated items and to achieve their better sequencing in the order of complexity.

Thus, further psycho- and neurolinguistic research on VAS characteristics may suggest which of them should be taken into account in selection and sequencing of treatment materials in complexity-based aphasia treatments. In addition to improvements in quantifying the complexity of treatment stimuli, VAS research can also inform the choice of treatment tasks in order to select those that can better target the core processes in verb production and comprehension. For example, if any evidence suggests that VAS processing is largely mediated by semantic properties of verbs, then treatment tasks should emphasize working with verb meanings and semantic and pragmatic contexts of verb use; if any evidence suggests that grammatical structure building and integration are more relevant to VAS processing, then treatment tasks should focus on building and transforming grammatical structures with verbs; if VAS processing appears to be highly automated and stays robust even in tasks that require superficial lexical access (such as lexical decision), then it may be most efficient to apply such single-word tasks in language treatment; etc.

Additionally, aphasia treatments can also be informed by research on specific neural correlates of VAS processing. Such research may suggest specific brain areas and networks as potential targets for brain stimulation interventions, which have been recently shown to be a promising approach in aphasia therapy (Monti et al., 2013). Administered concurrently with behavioral language therapy, brain stimulation may enhance therapy efficiency. Thus, it is particularly important to conduct research investigating neural correlates of various linguistic dimensions (in this case, specific VAS characteristics) in order to inform the choice of brain stimulation targets. Along the same lines, knowledge of specific neural correlates of VAS processing may inform protocols for intraoperative language mapping (Rofes & Miceli, 2014), for which verb tasks have been recently suggested to be more promising than noun tasks (Havas et al., 2015).

To summarize, individuals with aphasia show overall reduced performance on VAS processing, which likely underlies their reduced production and comprehension abilities. However, the effects of specific VAS characteristics show similar patterns in individuals with aphasia and in healthy speakers, suggesting quantitative deficits in access to VAS information rather than qualitative differences in its representation. This has mainly been demonstrated for the number of arguments, while other VAS characteristics have not been extensively studied in aphasia yet. Many agrammatism treatment approaches are based on selecting verbs with greater or smaller VAS complexity. Therefore, research that sheds light on whether and how understudied VAS dimensions impact verb complexity would have direct clinical implications for selecting treatment materials and for selecting treatment tasks. Additionally, research on neural correlates of VAS processing may suggest potential targets for brain stimulation treatments.

### 1.4. Interim summary and research hypotheses

Theoretical linguistics makes a distinction between verb arguments (that is, necessary components of the situation described by the verb) and adjuncts. Psycho- and neurolinguistic research confirms the psychological reality of this distinction, suggesting that arguments are more closely connected with the verb than adjuncts. The main question is what characteristics pertaining to verb arguments are stored and retrieved as part of the lexical entry of the verb, if any (a radical constructivist approach, as opposed to lexicalist approach, would state that there is no necessity to postulate a separate storage of any VAS information and that such information can always be inferred from the meaning of the verb).

Psycho- and neurolinguistic research has demonstrated behavioral and neural differences between the processing of verbs with different VAS characteristics. However, the number of arguments is the only VAS characteristic that has been extensively studied so far, whereas only a very limited body of research has addressed other VAS characteristics, such as thematic roles, subcategorization options and the overall number of number-of-argument frames of the verb. More research is warranted on whether these understudied VAS dimensions affect verb processing under different processing conditions; what is the nature of the additional processing load associated with them (whether it pertains to storage/retrieval and/or integration of VAS information), if any; and what specific brain structures are involved.

In the present research, VAS was characterized in terms of the following understudied VAS characteristics: the number of subcategorization options, the overall number of thematic options and the overall number of number-of-argument options. The number of subcategorization options was defined as the number of different grammatical classes that can serve as the verb's arguments. For example, the verb '*to complete'* has only one subcategorization option (it can only be followed by a noun phrase, *He completed the task*), whereas the verb '*to demand*' has more than one subcategorization option (it can be followed by a noun phrase, *He demanded a refund*, or a clause, *He demanded that they leave*, or an infinitive phrase, *He demanded to see them*). The number of number-of-argument options was defined as the overall number of options with regard to how many arguments a verb can be used with (e.g., some verbs can be used only intransitively, *The flowers bloomed*; some verbs can be used both intransitively and transitively, *The window opened* or *He opened the window*). The number of thematic options was defined as the overall number of options of the verb with regard to how syntactic positions (object of the sentence, subject of the sentence) can be assigned to thematic roles. For example, in some verbs the position of the subject can only correspond to the thematic role of an agent (*The girl sang* or *The girl sang a song* – in both cases '*the girl*' has a thematic role of an agent), whereas in other verbs the position of the subject can correspond to two thematic roles (agent or object) depending on the verb use (in *The door closed* the subject noun phrase *'the door'* has a patientive role and in *The teacher closed the door* the subject noun phrase *'the teacher'* has an agentive role).

Three experiments were conducted to investigate the effects of the three above VAS characteristics: two neuroimaging experiments (Experiment 1, using a sentence task, and Experiment 2, using a single-word task) and one behavioral experiment (Experiment 3, including both a sentence and a single-word task). It was hypothesized that a greater complexity in terms of any VAS options would result in a greater processing load and thus require additional neural activation and result in poorer behavioral performance, due to having to process a greater amount of linguistic information. Particularly in single-word tasks, this result would indicate that VAS options of the verb are stored as part of its lexical entry and are exhaustively accessed. If experiments reveal the opposite pattern (additional neural activation and poorer behavioral performance for verbs of lower VAS complexity), this would indicate that a greater VAS complexity may actually facilitate processing by "strengthening" verb representations and making them more "robust" or rich, or providing them with additional routes of lexical access by means of building more connections in the mental lexicon (similar to effects of semantic neighborhood density, e.g., Buchanan, Westbury & Burgess, 2001; Shaoul & Westbury, 2010). This may actually facilitate lexical access under processing conditions when not all of associated VAS information needs to be fully activated. Another possible outcome is that no effects of VAS characteristics would be found at the behavioral or neural level. This would indicate that VAS characteristics may not be a relevant parameter that affects representations of verbs in the mental lexicon.

Two different tasks (single-word-level and sentence-level processing conditions) were used because VAS access may differ depending on conditions: e.g., when the comprehender needs to integrate a verb into a specific sentential context vs. in processing isolated words outside any context pointing to a particular VAS option. Review of previous research on the most investigated VAS characteristic, the number of arguments, suggests that its behavioral effects may possibly be modulated by task; thus, other VAS characteristics also need to be studied in light of processing conditions. If similar effects of VAS are found in both a single-word-level and a sentence-level processing, this would indicate that VAS characteristics are exhaustively accessed regardless of processing conditions. If effects of any VAS characteristics are found in a single-word-level but not sentence-level task, this would suggest that potential VAS options of the verb are only exhaustively accessed when the context itself does not point to a particular VAS option; whereas in more restrictive conditions where a VAS option is selected by context, the other options are not retrieved. If effects of any VAS characteristics are found in a sentence-level but not single-word-level task, this would suggest that VAS options may be exhaustively retrieved in anticipation of upcoming sentence material, for the purposes of efficient sentence processing, whereas more ‘shallow’ single-word-level processing does not involve automated access to VAS options.

To recapitulate, this research aims to provide behavioral and neuroimaging data that will contribute to the understanding of what VAS properties are accessed under what conditions by language users and what brain regions their retrieval relies on. This research can have potential implications for theoretical linguistics, shedding light on what VAS information is stored as part of the verb’s lexical entry, as well as have clinical implications for brain stimulation and behavioral treatments of aphasia.

# CHAPTER 2

## EXPERIMENT 1: NEURAL CORRELATES OF VAS PROCESSING IN A SENTENCE-LEVEL TASK

Experiment 1 was a neuroimaging experiment investigating three understudied VAS characteristics in a sentence-level task: the number of subcategorization options, the number of thematic options and the number of number-of-argument options. The goal of the experiment was to test whether these characteristics are exhaustively accessed in sentence processing, as well as what is the nature of the additional load that they place (if any).

It was hypothesized that a greater complexity in terms of any VAS options would result in a greater processing load and thus require additional neural activation, due to having to process a greater amount of linguistic information. This result would indicate that VAS options of the verb are stored as part of its lexical entry, rather than only brought out when they are selected by context, and are exhaustively accessed in sentence processing, possibly as part of prediction of the incoming sentence material for the purposes of efficient sentence processing. If the experiment reveals the opposite pattern (additional neural activation for verbs of lower VAS complexity), this would indicate that a greater VAS complexity may actually facilitate processing, possibly because it provides verbs with a greater number of connections in the mental lexicon and makes their representations more robust and/or provides additional routes of lexical retrieval of these verbs (but not necessarily of all of their VAS options). Another possible outcome is that no effects of VAS characteristics would be found at the neural level. This would indicate that VAS characteristics may not be exhaustively accessed in sentence processing, where the context points to a particular VAS option.

If any additional brain activation is found for verbs of greater/lower VAS complexity, the location of activated brain areas can shed light on the nature of the additional processing load. The distinction of most interest was whether the additional load pertains to storage/retrieval of VAS options versus to structure building, selection and integration of VAS options in sentence context. To address this question, a region-of-interest (ROI) analysis was performed that included brain regions traditionally associated with these two broad functions. ‘Storage/retrieval areas’ included those identified in previous literature as involved in storage or retrieval of semantic information: left posterior superior temporal gyrus, posterior middle temporal gyrus, angular gyrus, supramarginal gyrus (all identified as major semantic processing areas in the meta-analysis of 120 neuroimaging studies by Binder, Desai, Graves, & Conant (2009)), as well as pars orbitalis of inferior frontal gyrus (Bookheimer, 2002; Gold & Buckner, 2002; Binder et al., 2009). ‘Integration areas’ included pars triangularis and opercularis of the left inferior frontal gyrus, which have been associated in previous literature with structure building and ordering (Hagoort, 2005; Friederici & Kotz, 2003; Meyer et al., 2012; Thompson & Meltzer-Asscher, 2014). It was assumed that if any group of verbs would be associated with increased activation in ‘integration’ areas, this would suggest that processing of the corresponding VAS characteristic places greater demands on integration/structure building. It was hypothesized that this may be the case for the number of subcategorization options and the number of number-of-argument options, since they both pertain to phrase structure. If any group of verbs would be associated with increased activation in ‘storage/retrieval’ areas, this would suggest that the corresponding VAS characteristic is associated with greater storage and/or retrieval demands. It was hypothesized that this may be the case for the number of thematic options, since it largely pertains to semantic properties of the verb. It is important to acknowledge that, according to the general principles of brain organization, brain areas included in the ROI analysis serve multiple functions in linguistic processing, rather than exclusively one function (see e.g. a discussion by Poldrack (2006)). Brain areas are included into ‘storage/retrieval’ or ‘integration’ group based on their function that appears more primary/frequent based on data from the previous literature but the approach is limited in that the activation of selected brain areas can only suggest possible underlying processes, rather than conclusively identify them.

To ensure that any potential neural effects cannot be ascribed to realization of arguments in a sentence, rather than their retrieval from verb representations, all of the verbs were used in the same syntactic structure. To maximally reduce any confounding by specific lexical items co-occurring with verbs, sentences were also matched on linguistic characteristics of all words used. This allowed us to investigate whether all VAS characteristics associated with the verbs’ lexical representations would still be activated even when not triggered by a specific context of verb use.

## 2.1. Method

### *2.1.1. Participants*

17 college-age participants participated in the study (10 females; mean age 23.4, SD 2.8, range 20-29; mean number of years of education 16.1, SD 2.2, range 12-21). For two participants, one out of the four scanning runs was excluded from the final analysis (one because of a technical issue with the scanner and one because of the participant misunderstanding the task at first). All participants were right-handed and native speakers of English. None of them reported a history of neurological or speech-language disorders. Participants either had normal vision or were fitted with MRI compatible glasses correcting it to normal. All participants signed an informed consent form prior to the study. All participants received monetary compensation. None of the participants had participated in Experiment 3 that included the same stimuli as this experiment.

### *2.1.2. Design*

The study included four groups of verbs. Group 1 (*complete*-verbs) included verbs that have only one number-of-argument option (can only be used transitively) and only one subcategorization option (can only be used with noun phrases and no other grammatical categories; e.g., *to abandon, to complete*). Group 2 (*demand*-verbs) included verbs that have only one number-of-arguments option (can only be used transitively) but, unlike *complete*-verbs, have multiple subcategorization options (can be used with either a noun phrase or at least one other subcategorization option, such as an infinitive and/or a dependent clause; e.g., *to promise*, *to demand*). Group 3 (*sing*-verbs) included verbs that have two number-of-argument options (can be used both intransitively and transitively) but only one thematic option (i.e., the role of the first argument does not differ between the transitive and intransitive use; e.g., *to clean, to embroider*: both in *The princess embroidered the pillow* and *The princess embroidered* the subject noun phrase '*the princess'* has a thematic role of an agent). This group corresponds to verbs that have been described in theoretical linguistics as undergoing unspecified object alternation (Levin, 1993). Group 4 (*break*-verbs) included verbs that have two number-of-argument options (can be used both intransitively and transitively), however, unlike *sing*-verbs, they have two thematic options (i.e., the role of the first argument differs between the transitive and intransitive use; e.g., *to open, to accelerate*: the thematic role of the subject noun phrase '*the man'* is different in '*The man accelerated*' and '*The man accelerated the vehicle'*). This group corresponds to verbs that have been described in theoretical linguistics as undergoing inchoative-causative alternation (Levin, 1993). VAS properties of the four experimental verb groups are summarized in Table 2.1.[6]

*Table 2.1*. Summary of experimental conditions.

| Group | Maximum number of arguments | Number of number-of-argument options | Number of thematic options | Number of subcategorization options |
|---|---|---|---|---|
| *complete*-verbs | 2 | 1 | 1 | 1 |
| *demand*-verbs | 2 | 1 | 1 | ≥2 |
| *sing*-verbs | 2 | 2 | 1 | (≥2, across number-of-argument frames) |
| *break*-verbs | 2 | 2 | 2 | (≥2, across number-of-argument frames) |

The study design allowed us to investigate several VAS properties by contrasting different verb groups. A contrast of *demand*-verbs over *complete*-verbs yields brain

[6] Note that these verbs groups are not verb classes in the sense of Levin (1993). Verbs are included into groups solely based on the similarity of investigated VAS characteristics; thus, verbs within each group may differ in terms of various semantic and grammatical properties.

activity associated with processing verb subcategorization options, since verbs in the *demand*-group have more subcategorization options than verbs in the *complete*-group, while other properties are equal. A contrast of *break*-verbs over *sing*-verbs yields brain activity associated with the number of thematic options, since *break*-verbs have a greater number of thematic options (the first argument can be either an agent or a patient) than *sing*-verbs, while other properties are equal. A contrast of *sing*-verbs over *complete*-verbs yields brain activity associated with the number of number-of-argument options, since *sing*-verbs have a greater number of number-of-argument options (two: intransitive and transitive use) than *complete*-verbs, while other properties are equal. It may appear that the contrast of *sing*-verbs versus *demand*-verbs could be used to investigate the number of number-of-argument options but in fact these two groups differ in how many subcategorization frames a verb has in a given number-of-argument frame (in a one-argument frame, *demand*-verbs have two subcategorization options and *sing*-verbs have one subcategorization option). Thus, any difference between these groups could actually be due to an effect of subcategorization options, whereas only one number-of-argument frame is in fact accessed. A contrast of *sing*-verbs versus *complete*-verbs is more appropriate, since both these groups have only one subcategorization frame in a given number-of-argument frame. Thus, any difference between these two groups would indicate that multiple number-of-argument frames are accessed (and, possibly, multiple subcategorization frames are accessed too but only as a consequence of accessing multiple number-of-argument frames). Experimental contrasts are summarized in Table 2.2.

*Table 2.2*. Summary of experimental contrasts.

| VAS characteristic | Contrast addressing the characteristic |
|---|---|
| Number of subcategorization options | *demand*-verbs > *complete*-verbs |
| Number of thematic options | *break*-verbs > *sing*-verbs |
| Number of number-of-argument options | *sing*-verbs > *complete*-verbs |

*2.1.3. Stimuli*

Experimental stimuli were sentences that included verbs from the above four groups. Each group included 20 verbs, used twice each, for an overall of 160 sentences. All sentences had the same structure and consisted of a subject noun phrase, a verb predicate in the past tense and an object noun phrase (e.g., *The user completed the survey; The buyer demanded a refund*; etc.). Sentences were matched across conditions on their overall length in the number of words and syllables, as well as on linguistic properties of verbs (lexical frequency based on the CELEX database (Baayen, Piepenbrock & Gulikers, 1995), length in syllables and letters, imageability (Coltheart, 1981)) and linguistic properties of object and subject nouns (lexical frequency based on the CELEX database (Baayen et al., 1995), imageability (Coltheart, 1981), number of singular/plural nouns, number of animate and inanimate nouns).

Additionally, since the task was to judge the well-formedness of sentences, stimuli included 80 not-well-formed filler sentences. Forty of them ("syntactic fillers") were not well-formed from the syntactic point of view, i.e., included an intransitive verb followed by a direct object (e.g., *The plan depended the weather*, *The group arrived the village*). The other 40 fillers ("semantic fillers") were not well-formed from the semantic point of view, i.e., included words that do not form a meaningful combination (e.g., *The* *test adored the flaws; The landlord announced the skirt*). Two different types of fillers were used to ensure that participants attended to both grammar and meaning of the stimuli. Even though fillers were not used in the analysis, they were also matched to experimental sentences on all of the linguistic properties listed above. Some of the verbs were repeated within fillers as well as across fillers and experimental sentences so that participants would not be able to strategically judge sentences based on whether they included a repeated verb, instead of attending to their content.

*2.1.4. Task*

The task was to silently read the sentences and to press a button if a sentence was not well-formed, i.e., either was not grammatical ("syntactic fillers") or was not meaningful ("semantic fillers"), while not pressing any buttons if a sentence was a well-formed sentence of the English language. The task was designed to not involve a motor response for experimental trials in order to eliminate any motor activity that may be confounding condition-related brain activity.

*2.1.5. Procedures*

Participants signed the consent form and underwent MRI safety screening. They were then given instructions and several examples and completed an out-of-scanner practice session consisting of ten items not used in the experiment. fMRI scanning was performed with a 3.0 T Siemens Tim Trio scanner at the McCausland Center for Brain Imaging. The stimuli were back projected on the computer screen. Participants were fitted with optical response buttons and pressed the button with their left index finger for not-well-formed sentences. E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm) was used for stimuli presentation and recording of the responses.

Participants first completed a T1-weighted anatomical MRI brain scan (TR = 2250 ms, TE = 4.52 ms, 256 x 256 matrix, 256 x 256 FOV, slice thickness = 1 mm, 176 axial slices) and then four runs of T2*-weighted multi-band EPI functional scanning (TR = 1550 ms, TE = 34 ms, 86 x 86 matrix, 215 x 215 FOV, slice thickness = 2.5 mm, 42 axial slices, 295 volumes). In the functional scans, an event-related design was used. Each run included 60 sentences, presented for 3 seconds with varying inter-stimulus interval (mean 4.5, SD 1.6, range 3.0-11.8 seconds), for an overall duration of each run of 7 minutes 37 seconds. Sequencing of conditions and selection of inter-stimulus intervals was optimized using the Optseq software (http://surfer.nmr.mgh.harvard.edu/optseq/). A fixation cross was presented in the center of the screen between the stimuli. The run order was ABCD in half of participants and DCBA in the other half of the participants. After each run, participants were given automated feedback showing them the percentage of accurate responses in this run.

### *2.1.6. Data analysis*

Behavioral data were analyzed in SPSS 22 software (http://www-01.ibm.com/software/analytics/spss), primarily for purposes of checking task compliance and potentially excluding participants who had low accuracy on the task. A repeated-measures ANOVA was performed on participants' accuracy across conditions.

fMRI data were analyzed in SPM8 software (http://www.fil.ion.ucl.ac.uk/spm/software/spm8). During preprocessing, functional scans were corrected for temporal order of slice acquisition and realigned to the mean functional volume. None of the participants had to be excluded from further analysis due to detection of excessive motion (i.e., greater than 3 mm in one direction) during the scanning. The anatomical volume was coregistered to the mean image and normalized to the Montreal Neurological Institute (MNI) 152-subject template brain using unified segmentation normalization, reslicing the volumes at the resolution of 3 x 3 x 3 mm. The functional volumes were then normalized using the same template and spatially smoothed with an 8 mm full-width half-maximum isotropic Gaussian kernel. In the first-level statistical analysis, a high-pass filter of 128 seconds was used to eliminate scanner drift. For each run, seven conditions were modeled (four experimental conditions, two filler conditions and errors as a separate condition) and six movement parameters obtained during pre-processing were entered as regressors. A canonical hemodynamic response function with a time derivative was used to model the blood oxygen level-dependent response to stimuli. Individual participants' binary brain images (created as the binarized sum of gray and white matter images obtained during the segmentation) were used as masks for inclusion of voxels into the analysis. Individual participants' summary activation maps for four experimental conditions were entered into a second-level repeated-measures analysis of variance (ANOVA) with experimental condition as an independent variable.

Three a priori planned paired *t*-tests were performed. One paired t-test contrasted *complete*-verbs and *demand*-verbs, aiming to yield brain activity associated with processing verb subcategorization options. The second paired t-test contrasted *complete*-verbs and *sing*-verbs, aiming to yield brain activity associated with processing number-of-argument options. The third paired t-test contrasted *sing*-verbs and *break*-verbs, aiming to yield brain activity associated with processing thematic options. A Monte Carlo simulation based on the 37584 voxels in our brain mask (the sum of the normalized grey and white matter segmentations of our participants) was performed with AlphaSim (http://afni.nimh.nih.gov/pub/dist/doc/program_help/AlphaSim.html), which yielded a cluster-size threshold of 17 contiguous voxels (459 $mm^3$) to correct for multiple comparisons at $\alpha = .05$ with a voxelwise threshold of $\alpha = .001$ (Friston et al., 1994; Forman et al., 1995). Anatomic labeling of resulting activation clusters was performed using the Automated Anatomical Labeling atlas and toolbox (Tzourio-Mazoyer et al., 2002).

Additionally, a region-of-interest (ROI) analysis was conducted to specifically address activation in a priori specified anatomical regions of interest: namely, areas that have been associated in previous literature with structure building and ordering (pars triangularis and opercularis of the left inferior frontal gyrus (Hagoort, 2005; Friederici & Kotz, 2003; Meyer et al., 2012; Thompson & Meltzer-Asscher, 2014)) and areas associated with semantic storage and/or retrieval (pars orbitalis of left inferior frontal gyrus (Bookheimer, 2002, Gold & Buckner, 2002), left posterior middle temporal, posterior superior temporal, angular and supramarginal gyri (Binder, Desai, Graves, & Conant, 2009)). ROI analyses were conducted with the MarsBaR toolbox in SPM (Brett, Anton, Valabregue, & Poline, 2002). For each subject and each region, average contrast values were obtained for the four experimental conditions. Contrast values are effect sizes and correspond to the beta weights associated with the conditions in the statistical model. These data were entered into seven repeated-measures ANOVAs with verb condition as a factor; a significant main effect of condition was followed up by three a priori defined pairwise comparisons of interest (same as in whole-brain analysis) with Bonferroni correction for multiple comparisons (resulting in $\alpha = 0.017$).

## 2.2. Results

### *2.2.1. Behavioral results*

The mean accuracy on all of the trials was 94.8% (SD 2.3%, range 90.4-99.2%). The mean accuracy on experimental conditions only (i.e., excluding fillers) was 95.9% (SD 2.5%, range 89.4-99.4%). A repeated-measures ANOVA on the accuracy in the four experimental conditions revealed a trend towards an effect of condition ($F(3,48) = 2.31$, $p = .088$). Bonferroni-corrected pairwise comparisons indicated that the trend was driven by *sing*-verbs tending to have higher accuracy than *complete*-verbs ($p = .151$) and *demand*-verbs ($p = .186$). Mean reaction time on the fillers was 1902 ms (SD 152 ms, range 1628-2156 ms).

### *2.2.2. Whole-brain fMRI analysis*

#### *2.2.4.1. Number of subcategorization options*

The paired t-test analysis of *complete*-verbs vs. *demand*-verbs (Figure 2.1) found clusters of increased activation associated with a greater number of subcategorization options (i.e., greater activation for *demand*-verbs than *complete*-verbs) in the left angular and supramarginal gyri, left posterior middle temporal gyrus, frontal superior and superior medial gyri, left precuneus and posterior cingulate gyrus, several subcortical structures, including left and right thalamus, right cerebellum, etc. The opposite contrast did not detect any clusters of increased activation associated with a lower number of subcategorization options (i.e., greater activation for *complete*-verbs than *demand*-verbs).

A full list of activation clusters is presented in Table 2.3. These are results from analysis with a cluster threshold correction for multiple comparisons; an FWE correction for multiple comparisons results in smaller clusters in the left cingulum and precuneus, left middle temporal gyrus and left angular gyrus for verbs with a greater number of subcategorization options compared to verbs with a lower number of subcategorization options.

*Table 2.3*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in activation clusters associated with a greater number of subcategorization options (*demand*-verbs > *complete*-verbs) ($p < .05$; cluster size > 17).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Posterior cingulum | Precuneus, middle and posterior cingulum | -12 | -49 | -28 | 172 | 6.76 |
| L | Angular gyrus | Middle temporal gyrus, superior temporal gyrus, angular gyrus, supramarginal gyrus | -54 | -61 | 25 | 132 | 6.71 |
| L | Middle temporal gyrus | Middle temporal gyrus, superior temporal pole | -60 | -40 | 1 | 190 | 6.17 |
| L | Superior medial frontal gyrus | Superior frontal gyrus, superior medial frontal gyrus | -9 | 56 | 28 | 70 | 5.22 |
| L, R | Thalamus | Left and right thalamus, right caudate nucleus, right pallidum | -9 | -31 | 4 | 165 | 4.85 |
| R | Cerebellum | Cerebellum | 6 | -49 | -44 | 19 | 4.53 |
| R | Cerebellum | Cerebellum | 30 | -55 | -38 | 29 | 4.48 |
| R | Middle temporal gyrus | Middle temporal gyrus, superior temporal gyrus | 45 | -34 | -2 | 29 | 4.48 |
| R | Superior temporal gyrus | Middle temporal gyrus, superior temporal gyrus | 54 | -10 | -14 | 19 | 4.30 |
| R | Calcarine gyrus | Lingual gyrus. inferior occipital gyrus, calcarine gyrus, fusiform gyrus | 21 | -91 | -2 | 31 | 4.11 |

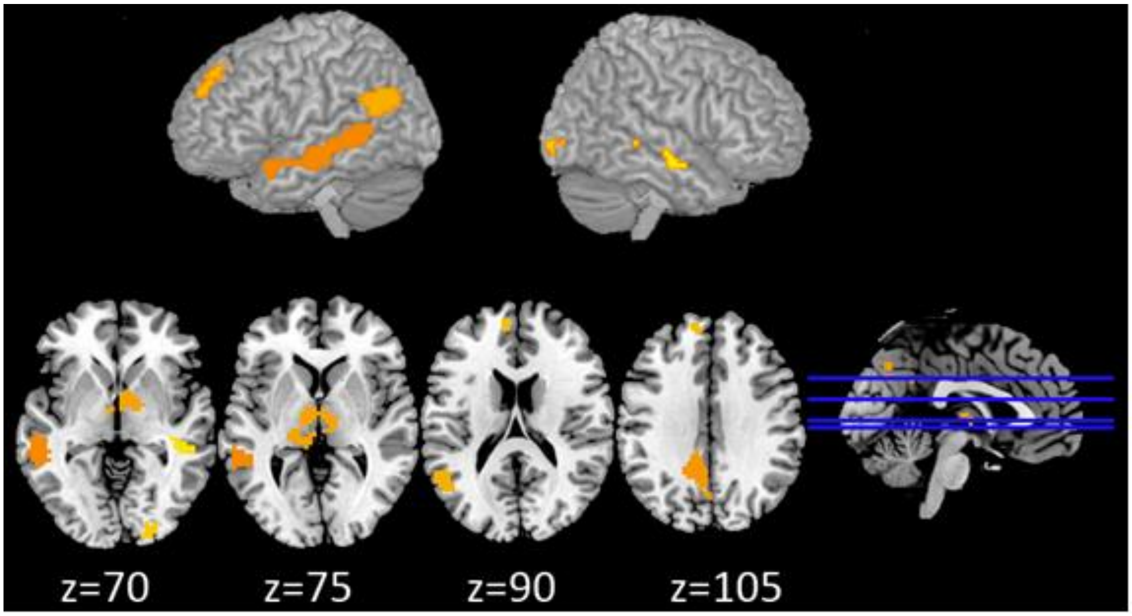


*Figure 2.1*. Brain areas showing increased activation associated with a greater number of subcategorization options (*demand*-verbs > *complete*-verbs) (voxelwise $p < .001$; cluster size > 17).

*2.2.4.2. Number of thematic options*

The paired *t*-test analysis of *break*-verbs vs. *sing*-verbs found clusters of increased activation associated with a greater number of thematic options (i.e., greater activation for *break*-verbs than *sing*-verbs) in white matter underlying left inferior frontal gyrus, in left caudate nucleus and left middle cingulum (Figure 2.2, red colors). The opposite contrast found areas of increased activation associated with a lower number of thematic options (i.e., greater activation for *sing*-verbs than *break*-verbs) at the junction of the right angular, superior temporal and middle temporal gyri (Figure 2.2, blue colors). A full list of activation clusters is presented in Tables 2.4 and 2.5. These are results from analysis with a cluster threshold correction for multiple comparisons; no voxels survived an FWE correction for multiple comparisons.

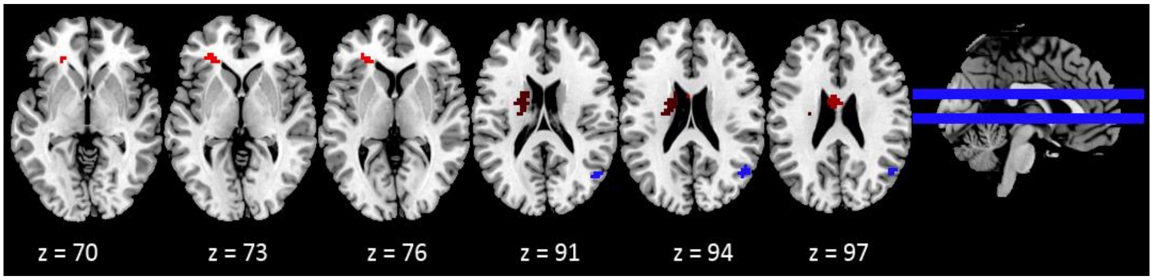


*Figure 2.2*. Brain areas showing increased activation associated with a greater number of thematic options (*break*-verbs > *sing*-verbs; red color) and a lower number of thematic options (*sing*-verbs > *break*-verbs; blue color) (voxelwise $p < .001$; cluster size > 17)

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Middle cingulum | Middle cingulum | -6 | -4 | 28 | 35 | 4.46 |
| L | Caudate nucleus | Caudate nucleus | -18 | -7 | 22 | 41 | 3.94 |
| L | White matter underlying pars orbitalis / triangularis of the left inferior frontal gyrus[7] | | -27 | 35 | 4 | 20 | 3.89 |

*Table 2.4*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in activation clusters associated with a greater number of thematic options (*break*-verbs > *sing*-verbs) (voxelwise $p < .001$; cluster size > 17).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| R | Angular gyrus | Middle temporal gyrus, superior temporal gyrus, angular gyrus | 51 | -64 | 25 | 25 | 3.70 |

*Table 2.5*. AAL regions, MNI coordinates, cluster size and maximal t-values for local maxima in activation clusters associated with a lower number of thematic options (sing-verbs > break-verbs) (voxelwise p < .001; cluster size > 17).

*2.2.4.3. Number of number-of-argument options*

The paired t-test analysis of *sing*-verbs vs. *complete*-verbs (Figure 2.3) did not detect any increased activation associated with a greater number of number-of-argument options (i.e., greater activation for *sing*-verbs than *complete*-verbs). The opposite contrast

[7] Since automated labeling found a large part of the cluster to lie outside the gray-matter areas included in the atlas, the judgment of their location was based on visually reviewing the activation.

revealed a cluster of increased activation associated with a lower number of number-of-argument options (i.e., greater activation for *complete*-verbs than *sing*-verbs) in the left superior frontal gyrus and supplementary motor area. A full list of activation clusters is presented in Table 2.6. These are results from analysis with a cluster threshold correction for multiple comparisons; no voxels survived an FWE correction for multiple comparisons.

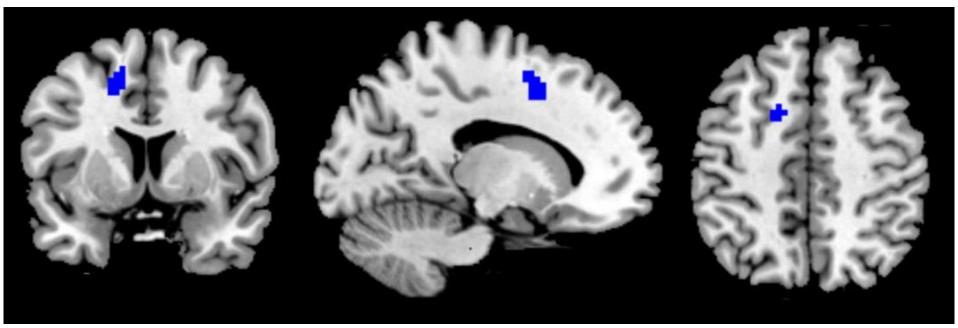

*Figure 2.3*. Brain areas showing increased activation associated with a lower number of number-of-argument options (*complete*-verbs > *sing*-verbs) (voxelwise $p < .001$; cluster size > 17).

*Table 2.6*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in activation clusters associated with a lower number of number-of-argument options (*complete*-verbs > *sing*-verbs) (p < .05; cluster size > 17).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Superior frontal gyrus | Superior frontal gyrus, supplementary motor area | -15 | 8 | 46 | 31 | 4.94 |

*2.2.3. ROI fMRI analysis*

Mean contrast values in the four verb conditions in the seven regions-of-interest are presented in Figure 2.4.

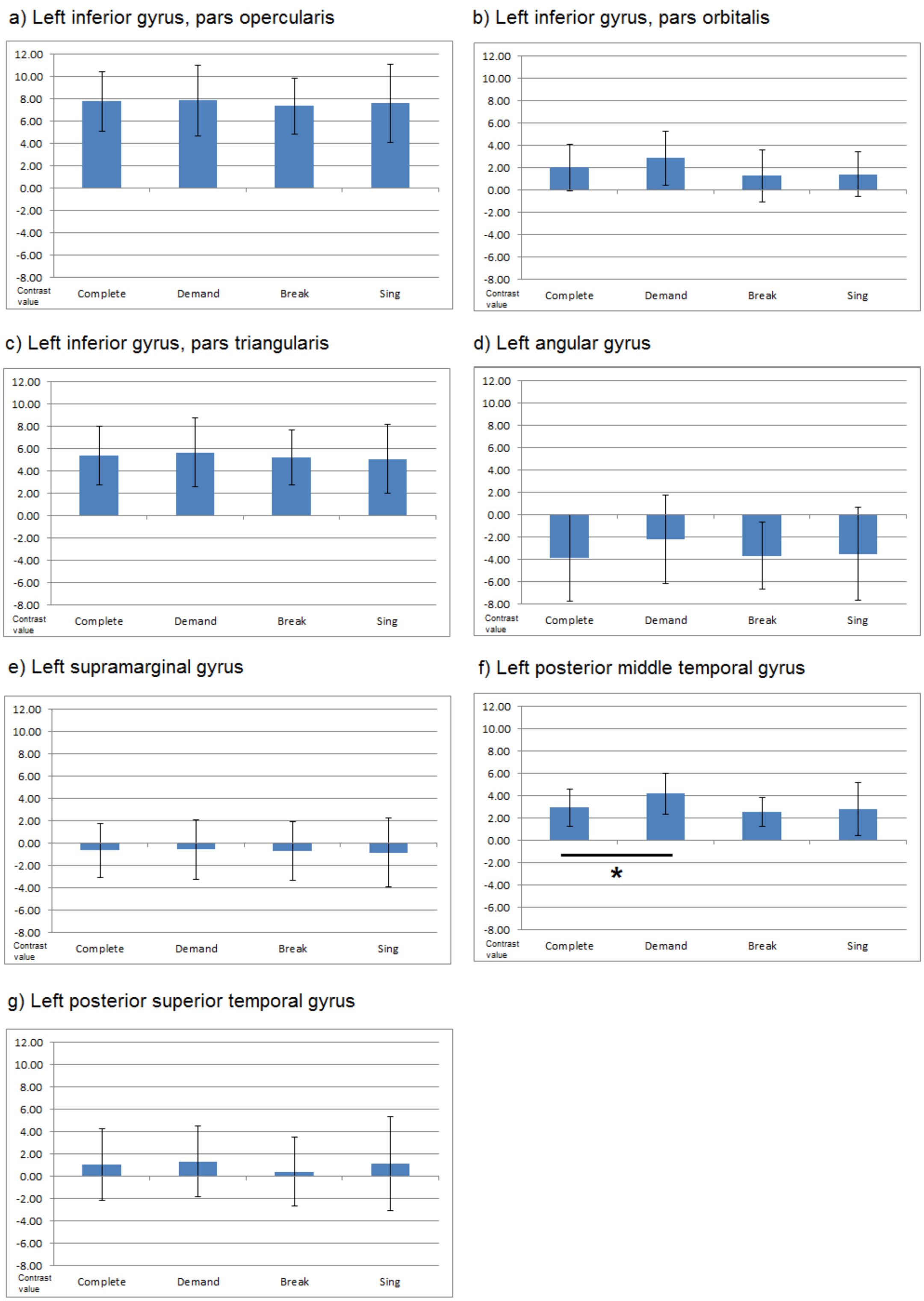


*Figure 2.4.* Mean contrast values in the four verb conditions in the seven regions-of-interest in Experiment 1. Error bars indicate the standard error of the mean. * indicates a priori planned pairwise comparisons that were significant after Bonferroni correction for multiple comparisons ($p < .017$).

Repeated-measures ANOVAs found significant effects of verb condition in the pars orbitalis of the left inferior frontal gyrus ($F(1,3) = 4.94$, $p = .005$), left posterior middle temporal gyrus ($F(1,3) = 6.14$, $p = .001$), as well as a statistical trend in the left angular gyrus ($F(1,3) = 2.35$, $p = .084$). For pars orbitalis of the left inferior frontal gyrus, none of the planned follow-up pairwise comparisons were significant after Bonferroni correction for multiple comparisons. For left posterior middle temporal gyrus, follow-up pairwise comparisons revealed greater contrast values associated with a greater number of subcategorization options, i. e., in *demand*-verbs compared to *complete*-verbs ($p = .001$). For left angular gyrus, none of the planned follow-up pairwise comparisons were significant after Bonferroni correction for multiple comparisons. Note that *demand*-verbs showed the greatest contrast values not only in the left posterior middle temporal gyrus, where their comparison to *complete*-verbs was significant, but also in the two regions (pars orbitalis of left inferior frontal gyrus, left angular gyrus) where pairwise comparisons did not reach significance after correction for multiple comparisons. The effect of verb condition was not significant in the other four regions of interest (pars triangularis of the left inferior frontal gyrus, pars opercularis of the left inferior frontal gyrus, left posterior superior temporal gyrus, left supramarginal gyrus).

### 2.3. Discussion

Experiment 1 used fMRI to investigate the neural correlates of three understudied VAS characteristics (number of subcategorization options, number of thematic options and the overall number of number-of-argument options) in a sentence processing task. All of the verbs were used in the same syntactic sentence context to ensure that any neural effects reflect VAS processing rather than the processing of the sentential context.

To summarize the results of Experiment 1, for two out of three investigated VAS characteristics (number of subcategorization options and number of thematic options, but not number of number-of-argument options), the analysis found areas of increased activation for more complex verbs. Unexpectedly, for two out of three investigated VAS characteristics (number of thematic options and number of number-of-argument options, but not number of subcategorization options), the analysis also found areas that showed increased activation for *less* complex verbs. At a more conservative statistical threshold (FWE rather than cluster-threshold correction for multiple comparisons), the only finding that retained significance was a greater activation for a greater number of subcategorization options. The findings for each VAS characteristic are discussed in more detail below.

*2.3.1. Number of subcategorization options*

A greater number of subcategorization options was associated with a greater activation in several areas of the left hemisphere (superior frontal gyrus and temporo-parietal junction extending to the posterior middle temporal gyrus) in the whole-brain analysis; the ROI analysis found increased activation in one ROI categorized as involved in semantic storage/retrieval (left posterior middle temporal gyrus). Increased activation for verbs of greater VAS complexity was consistent with the initial hypothesis, indicating that subcategorization options of the verb are stored as part of its lexical entry, rather than are only brought out by context where this particular option is selected, and are exhaustively accessed in sentence processing. The localization of the effect (discussed in more detail below) suggests that the increased activation is associated with accessing additional information as part of accessing lexical knowledge about the verb. The result was robust, with part of activation surviving an FWE correction for multiple comparisons.

Specific brain areas showing increased activation for a greater number of subcategorization options are only partially consistent with the findings of previous neuroimaging studies of the number of subcategorization options that also used sentence tasks. The present study did not find activation in left superior temporal gyrus, as in Shetreet et al. (2007, 2010) although there was activation in the adjacent left posterior middle temporal gyrus. However, the activation at the temporo-parietal junction found in the present study is reminiscent of results of earlier studies that investigated other VAS characteristics such as the number of arguments (Den Ouden et al., 2009; Thompson et al. 2007) or the number of thematic options (Meltzer-Asscher et al., 2013; they also showed a superior frontal gyrus activation, similarly to the present study). Activation at the temporo-parietal junction has been interpreted in previous literature as pertaining to semantic storage / retrieval, rather than structure building and ordering (Meyer et al., 2012; Thompson & Meltzer-Asscher, 2014). In line with this, activation found in the pars orbitalis of the left inferior frontal gyrus is also likely to pertain to semantic storage and/or retrieval (Bookheimer, 2002, Gold & Buckner, 2002). Thus, all of the areas that were activated in association with a greater number of subcategorization options seem to reflect semantic storage and/or retrieval, rather than structure building, as was originally hypothesized. These findings point to a greater semantic storage/retrieval load associated with processing verbs with a greater number of subcategorization options. Such verbs may contain more information in their lexical entries which is exhaustively accessed at the point when the verb is encountered in a sentence. More information needs to be retrieved, leading to increased engagement of several left-hemisphere brain areas. One way to view the retrieval of multiple potential subcategorization options of the verb is that comprehenders engage in prediction of the complement that follows the verb (Kamide, 2008). Thus, information on possible subcategorization options of the verb becomes available, even if not all of them are actively used.

### *2.3.2. Number of thematic options*

A greater number of thematic options was associated with a small cluster of activation in the left cingulum, as well as in white matter underlying pars orbitalis and, to a smaller extent, pars triangularis of the left inferior frontal gyrus in the whole-brain analysis; the ROI analysis did not find regions of increased activation. The result was consistent with the initial hypothesis and indicates that thematic options of the verb are stored as part of its lexical entry, rather than only brought out by context where this particular VAS option is selected, and are exhaustively accessed in sentence processing. However, the precise location of activation does not allow to distinguish whether the nature of the additional processing load associated with a greater number of thematic roles has more to do with semantic storage/retrieval (i.e., more information on thematic roles needs to be retrieved; this could be the role of pars orbitalis of left inferior frontal gyrus) or with integration/structure building (i.e., selecting thematic roles appropriate for sentence context is more challenging; this could be the role of pars triangularis of left inferior frontal gyrus). To the best of our knowledge, the number of thematic options has not yet been investigated in sentence-level tasks; thus, no data from previous literature are available for comparison.

A smaller number of thematic options was associated with greater activation in the right angular gyrus in the whole-brain analysis; the ROI analysis did not find regions of increased activation. This was not a hypothesized result but one may speculate that it may reflect a more “creative” language comprehension process triggered when encountering the object of *sing*-verbs. Since both their transitive and intransitive use imply the same thematic role of the subject of the sentence, the “basic” entry of the verb may contain only the intransitive frame, with the semantics of an activity in general (“pragmatic focus on the activity itself”, Rice, 1988, p. 206), whereas the transitive use may place greater demands on online integration of the object when it is present. Note that Shetreet et al. (2010) make a contrary suggestion. They also suggest that “optional” verbs may be processed as having only one frame, but they argue that this one frame is transitive, whereas the use of these verbs in an intransitive frame is made possible by mechanisms of thematic saturation (Rizzi, 1986; Reinhart, 2000) in online processing.

### *2.3.3. Number of number-of-argument options*

A greater number of number-of-argument options was not associated with additional neural activation in any brain areas in either whole-brain or ROI analysis, contrary to the hypothesis. The experiment did not find any evidence of exhaustive access to all number-of-argument options in sentence processing and thus indicates that they are either not exhaustively accessed in sentence processing or possibly not stored as part of the lexical entry of the verb at all, in line with the findings by Meltzer-Asscher et al. (2015) and Shetreet et al. (2010).

A lower number of number-of-argument options was associated with increased activation in the left superior frontal gyrus in the whole-brain analysis; the ROI analysis did not find regions of increased activation. One may again speculate that a smaller amount of information and connections in the mental lexicon for lower-complexity verbs may make their representations less “robust” / “rich” and thus more difficult to access, requiring additional neural recruitment. The question remains, however, why this additional activation was localized to the left superior frontal gyrus, which has not been commonly associated with language processing: this may reflect greater demands for general attentional/executive processes The findings are partially consistent with the results by Shetreet et al. (2010), who also found an increased activation for verbs with a lower number of number-of-argument options presented with a complement but in different brain areas than in the present experiment (left superior and middle temporal, middle frontal gyri), but not Shetreet et al. (2007) who did not find areas of increased activation for a lower number of number-of-argument options. The discrepancy may be due to a different approach to analysis: Shetreet et al. (2007) used a parametric analysis, using verbs with one, two and three number-of-argument options and looking for graded activation, whereas our Experiment 1 and Shetreet et al. (2010) relied on binary comparisons of verbs with one vs. two options..

### *2.3.4. Conclusions*

Experiment 1 suggests that subcategorization options and thematic options of the verb are exhaustively accessed in sentence processing. A greater number of subcategorization options possibly places an additional load on lexical-semantic storage/retrieval, while the nature of the additional load placed by a greater number of thematic options is not known yet. The number-of-argument options do not appear to be exhaustively accessed in sentence processing. The findings also suggest that in some cases a greater number of VAS options (thematic options and number-of-argument options) may facilitate verb processing, possibly by providing a verb with a greater number of connections in the mental lexicon and thus with additional routes of lexical access to these verbs (but not necessarily to all of their VAS options).

Importantly, these findings only pertain to sentence level processing, where language users engage in prediction of incoming sentence material for the purposes of efficient processing but are ultimately presented with only one VAS selected in the context. It is quite possible that VAS access is different under other processing conditions, for example, in single-word processing, where no particular VAS option is selected by context. VAS access under such conditions is investigated in Experiment 2, which is a neuroimaging experiment that has an identical design to Experiment 1 but uses a single-word-level task. Comparing results of Experiments 1 and 2 may provide us with better understanding of the mechanisms of VAS access depending on processing conditions.

# CHAPTER 3

## EXPERIMENT 2: NEURAL CORRELATES OF VAS PROCESSING IN A SINGLE-WORD-LEVEL TASK

Experiment 2 was a neuroimaging experiment that aimed to investigate neural correlates of VAS in healthy speakers at the single-word processing level. The goal of the experiment was to test whether these characteristics are stored as part of lexical knowledge about the verb and exhaustively accessed in single-word-level processing, as well as what is the nature of the additional load that they place (if any).

Specific VAS characteristics of interest were the same as in the neuroimaging Experiment 1: number of subcategorization options of the verb, its total number of thematic options and its total number of number-of-argument options. However, it is highly likely that VAS properties are accessed differently depending on verb processing conditions. In sentence level processing, language users likely engage in prediction of incoming sentence material for the purposes of efficient processing but are ultimately presented with only one VAS option that is used in this context. It is quite possible that VAS access is different under other processing conditions, for example, in single-word processing, where no particular VAS option is selected by context. Comparing effects of VAS characteristics in sentence-level processing (investigated in Experiment 1) and in single-word-level processing (investigated in Experiment 2) may provide us with better understanding of the mechanisms of VAS access depending on processing conditions, which may have important implications for selection of tasks in language therapies aiming to improve verb processing.

It was hypothesized that a greater complexity in terms of any VAS options would result in a greater processing load and thus require additional neural activation, due to having to process a greater amount of linguistic information. This result would indicate that VAS options of the verb are stored as part of its lexical entry and are exhaustively accessed in single-word-level processing. If the experiment reveals the opposite pattern (additional neural activation for verbs of lower VAS complexity), this would indicate that a greater VAS complexity may actually facilitate processing, possibly because it provides verbs with a greater number of connections in the mental lexicon and makes their representations more robust and/or provides additional routes of lexical retrieval of these verbs (but not necessarily of all of their VAS options). Another possible outcome is that no effects of VAS characteristics would be found at the neural level. This would indicate that VAS characteristics may not be exhaustively accessed in single-word-level processing, where, in contrast to sentence processing, retrieval of these characteristics is not likely to contribute to efficient processing.

If any additional brain activation is found for verbs of greater/lower VAS complexity, the location of activated brain areas can shed light on the nature of the additional processing load. The distinction of most interest was whether the additional load pertains to storage/retrieval of VAS options versus to structure building, selection and integration of VAS options. To address this question, a region-of-interest (ROI) analysis was performed that included brain regions traditionally associated with these two broad functions: see the introduction to Section 2 and Section 2.1.6 for a list of ROIs and motivation of their selection. It was hypothesized that any increased activation would be localized to regions associated with lexical-semantic storage/retrieval, since integration processes do not appear relevant for processing of isolated words. If any activation is found in regions associated with integration, this would suggest that access to VAS information may initiate the building of a sentence frame, even if not required by the task.

## 3.1. Method

### *3.1.1. Participants*

23 neurologically healthy young participants participated in the study overall; however, one was excluded due to excessive head motion during the experiment and one due to an incidental finding. Thus, the analyzed sample included 21 participants (12 females; mean age 22.9, SD 2.8, range 19-30; mean number of years of formal education 16.0, SD 1.8, range 12-19). All participants were right-handed and native speakers of English. Participants with a reported history of neurological or speech-language disorders or any contraindications to MRI were not included in the study. Participants either had normal vision or were fitted with MRI compatible glasses correcting it to normal. All participants signed an informed consent form prior to the experiment. All participants received monetary compensation.

### *3.1.2. Design*

Design of the study was identical to Experiment 1 and included the same four experimental groups of verbs, allowing to perform the same contrasts (please refer to Section 2.1.2).

### *3.1.3. Stimuli*

Stimuli of the study included 20 verbs from each group, for a total of 80 verbs (full list of verb stimuli along with a justification of their inclusion into experimental groups is presented in Appendix 1), and 120 non-words. The word to non-word ratio was set to 2:3 because it was expected that compared to 1:1 ratio, it would reduce reliance on probabilistic processing strategies, make verbs more salient and lead to their deeper processing (similar to "oddball" paradigms in event-related potentials research, (Squires, Squires & Hillyard, 1975)). In order to increase the number of trials and thus power without compromising the matching of conditions by adding not ideally matched items, each item was repeated twice in the study. All stimuli were preceded by "*to*" (e.g., "*to break*" rather than "*break*") to ensure their unambiguous interpretation as verbs. Verb groups were matched for lexical frequency based on the CELEX database (Baayen et al., 1995), length in syllables and letters, orthographic neighborhood size (Medler & Binder, 2005) and imageability, according to ratings obtained through a preliminary online survey described below. Non-words were pronounceable and were formed by re-combining pronounceable segments of experimental verbs. Non-words were matched to verbs on length in syllables and letters and on the orthographic neighborhood size (Medler & Binder, 2005).

Although existing psycholinguistic databases (such as the MRC Psycholinguistics Database, (Coltheart, 1981)) do include imageability ratings, none of them, to the best of our knowledge, provide separate ratings for different grammatical classes of word forms (e. g., they would only provide one rating for "break" rather than two separate ratings for "to break" and "a break"). This can lead to inaccurate assessment of imageability specific to verbs. Thus, a survey was conducted where stimuli were presented with a verb particle "to" (e.g., "*to break*", rather than "*break*") and participants were specifically asked to assess the imageability of an action on a scale from 1 (not imageable) to 7 (highly imageable). Since most verbs intended for use in Experiments 1 and 2 have relatively abstract semantics, the survey included 10 imageable fillers (e. g., "*to kiss*", "*to swim*") in order to provide participants with a more diverse sample of stimuli and avoid bias (overestimating the imageability of relatively abstract verbs due to lack of opportunity for comparison). The survey was completed by 45 native speakers of English (43 females; mean age 28.0, SD 8.2, range 22-52) with no reported history of neurological, speech, language, hearing or reading disorders on a voluntary basis or for extra course credit.

*3.1.4. Task*

The task was to silently read strings of letters presented on the screen and to press one button if a string of letters made a real word of the English language or to press another button if a string of letters did not make a real word of the English language. Unlike Experiment 1, Experiment 2 included an overt response (pressing a button) for both fillers (non-words) and experimental stimuli (real words). The motivation for this was that the stimuli included more non-words than real words and we wanted to avoid any effect of inhibiting a response for real words; also, this made it possible to collect and analyze full behavioral data.

*3.1.5. Procedures*

Participants signed an informed consent form and underwent MRI safety screening. Then they were given instructions and several examples and completed an out-of-scanner practice session that consisted of 25 items not used in the experiment. Brain scanning was performed with a 3.0 T Siemens Tim Trio scanner at the McCausland Center for Brain Imaging. The stimuli were back projected on the computer screen. Participants were fitted with optical response buttons. E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm) was used for the presentation of stimuli and recording of the responses.

Participants first completed a T1-weighted anatomical MRI scan (TR = 2250 ms, TE = 4.52 ms, 256 x 256 matrix, 256 x 256 FOV, slice thickness = 1 mm, 176 axial slices) and then 4 runs of T2*-weighted multi-band EPI functional scanning for the lexical decision task (327 volumes, TR = 1550 ms, TE = 34 ms, 86 x 86 matrix, 215 x 215 FOV, slice thickness = 2.5 mm, 42 axial slices), each lasting about 8 minutes 45 seconds. Event-related design was used. Each lexical decision run included 100 items, presented for 1.5 seconds with varying inter-stimulus interval (minimum 1.5 seconds and an average of approximately 3.5 seconds). Sequencing of conditions and selection of inter-stimulus intervals was optimized using the Optseq software (http://surfer.nmr.mgh.harvard.edu/optseq/). A fixation cross was presented in the center of the screen between the stimuli. The run order was ABCD in half of participants and CDAB in the other half of the participants. Items from runs A and B were repeated in runs C and D but in a different order. All runs were balanced on all the linguistic characteristics of verbs (lexical frequency based on the CELEX database (Baayen et al., 1995), length in syllables and letters, imageability (as measured in the preliminary online survey, described above in the Experiment 1 section), orthographic neighborhood size (Medler & Binder, 2005) and on characteristics of non-words (length in syllables and letters and orthographic neighborhood size). After each run, participants were given automated feedback showing them the percentage of accurate responses in this run.

### *3.1.6. Data analysis*

#### *3.1.6.1. Behavioral data analysis*

Reaction times and accuracy were analyzed. Only correct responses were included into the analysis of reaction times. Accuracy values were log-transformed prior to statistical tests (Bartlett, 1947; Hoyle, 1973). The following a priori planned paired *t*-tests were performed: a test comparing *demand*-verbs vs. *complete*-verbs to investigate an effect of subcategorization options, a test comparing *complete*-verbs vs. *sing*-verbs to investigate an effect of the number of number-of-argument options, and a test comparing *sing*-verbs vs. *break*-verbs to investigate the number of thematic options. These were performed on average participants' accuracy and reaction times as paired *t*-tests in the SPSS 22 software (http://www-01.ibm.com/software/analytics/spss). For each outcome measure, Bonferroni correction for multiple comparisons was used, resulting in $\alpha = .017$ for an overall significance level of $\alpha = .05$.

#### *3.1.6.2. fMRI data analysis*

fMRI data were analyzed in SPM8 software (http://www.fil.ion.ucl.ac.uk/spm/software/spm8). During preprocessing, functional scans were corrected for temporal order of slice acquisition and realigned to the mean functional volume. Participants were excluded from further analysis if their head motion is greater than 3.0 mm in any direction during the scanning[8]. The anatomical volume was coregistered to the mean image and normalized to the Montreal Neurological Institute (MNI) 152-subject template brain using unified segmentation normalization, reslicing the volumes at the resolution of 3 x 3 x 3 mm. The functional volumes were then normalized using the same template and spatially smoothed with an 8 mm full-width half-maximum isotropic Gaussian kernel.

In the first-level statistical analysis of lexical decision runs, a high-pass filter of 128 seconds was used to eliminate scanner drift. For each run, six conditions were modeled (four experimental conditions, one non-word condition and errors as a separate condition) and six movement parameters obtained during pre-processing were entered as regressors. An additional regressor was based on participants' trial-specific reaction times and was obtained by creating a separate general linear model for each participant, with one condition type (collapsing across the six conditions) parametrically modulated by response time. A canonical hemodynamic response function with a time derivative was used to model the blood oxygen level-dependent response to stimuli. Individual participants' binary brain images were used as masks for inclusion of voxels into analysis.

Individual participants' summary activation maps for four experimental conditions were entered into the second-level analysis. Three a priori planned paired comparisons within a repeated-measures ANOVA model were performed. One paired t-test contrasted *complete*-verbs and *demand*-verbs, aiming to yield brain activity associated with processing verb subcategorization options. The second paired t-test contrasted *complete*-verbs and *sing*-verbs, aiming to brain activity associated with

[8] With an exception of one participant who moved his head along z-axis by approximately 3.5 mm in one of four runs but whose data were still included into analysis since the motion criterion was only exceeded very slightly.

number-of-argument options. The third paired t-test contrasted *sing*-verbs and *break*-verbs, aiming to yield brain activity associated with processing semantic argument frames. A Monte Carlo simulation based on the average brain mask of the normalized grey and white matter segmentations of our participants was performed with AlphaSim (http://afni.nimh.nih.gov/pub/dist/doc/program_help/AlphaSim.html) to establish a cluster-size threshold for multiple comparison correction (Friston et al., 1994; Forman et al., 1995). It yielded a cluster-size threshold of 27 contiguous voxels (459 $mm^3$) to correct for multiple comparisons at $\alpha = .05$ with a voxelwise threshold of $\alpha = .001$. Anatomic labeling of resulting activation clusters was performed using the Automated Anatomical Labeling atlas and toolbox (Tzourio-Mazoyer et al., 2002).

Additionally, a region-of-interest (ROI) analysis was conducted to specifically address activation in a priori specified anatomical regions of interest: namely, areas that have been associated in previous literature with structure building and ordering (pars triangularis and opercularis of the left inferior frontal gyrus (Hagoort, 2005; Friederici & Kotz, 2003; Meyer et al., 2012; Thompson & Meltzer-Asscher, 2014)) and areas associated with semantic storage and/or retrieval (pars orbitalis of left inferior frontal gyrus (Bookheimer, 2002, Gold & Buckner, 2002), left posterior middle temporal, posterior superior temporal, angular and supramarginal gyri (Binder, Desai, Graves, & Conant, 2009)). ROI analyses were conducted with the MarsBaR toolbox in SPM (Brett, Anton, Valabregue, & Poline, 2002). For each subject and each region, average percent signal change was obtained for the four experimental verb conditions. These data were entered into seven repeated-measures ANOVAs with verb condition as a factor; a significant main effect of condition was followed up by three a priori defined pairwise comparisons of interest (same as in whole brain analysis) with Bonferroni correction for multiple comparisons (resulting in $\alpha = 0.017$).

## 3.2. Results

### *3.2.1. Behavioral results*

The participants' accuracy on the lexical decision task was 97.8 % on average (SD 4.0 %, range 81.5 – 100.0 %). Average reaction time was 805 ms (SD 84 ms, range 695-1023 ms). No participants were excluded from the analysis due to low performance. Average accuracy and reaction times in each experimental condition in Experiment 2 are presented in Table 3.1.

*Table 3.1.* Average accuracy and reaction time in Experiment 2, mean (SD).

| | *Complete*-verbs | *Demand*-verbs | *Sing*-verbs | *Break*-verbs | Non-words |
|---|---|---|---|---|---|
| Accuracy | 94.6 % (2.0 %) | 95.2 % (2.0 %) | 92.3 % (1.9 %) | 94.6 % (2.0 %) | 97.3 % (6.5 %) |
| Reaction time | 759 ms (80 ms) | 726 ms (70 ms) | 766 ms (73 ms) | 756 ms (74 ms) | 840 ms (101 ms) |

The three Bonferroni-corrected planned *t*-tests on reaction times revealed that verbs with a greater number of subcategorization options (*demand*-verbs) had significantly faster reaction times than verbs with a lower number of subcategorization options (*complete*-verbs) ($t(20) = 4.62$, $p < .001$); there were no significant effects of the number of thematic options (*sing*-verbs vs. *break*-verbs) ($t(20) = 1.48$, $p = .154$) or the number of number-or-argument options (*sing*-verbs vs. *complete*-verbs) ($t(20) = 1.00$, $p = .330$) on reaction times. The three Bonferroni-corrected planned *t*-tests on accuracy revealed that verbs with a greater number of thematic options (*break*-verbs) showed higher accuracy than verbs with a lower number of thematic options (*sing*-verbs) ($t(20) = 3.24$, $p = .004$); verbs with a greater number of number-of-argument options (*sing*-verbs) showed lower accuracy than verbs with a lower number of number-of-argument options (*complete*-verbs) ($t(20) = 2.82$, $p = .004$); no effect of the number of subcategorization options (*complete*-verbs vs. *demand*-verbs) was revealed in accuracy ($t(20) = 1.70$, $p = .104$).

### *3.2.2. Whole-brain fMRI analysis*

#### *3.2.2.1. Words versus non-words*

The contrast of all verb conditions vs. non-words found clusters of greater activation for verbs than non-words in a large bilateral network of frontal, temporal, parietal and occipital areas (Figure 3.1, red colors; Table 3.2). Clusters of greater activation for non-words than words were located in the left frontal lobe and right hippocampus (Figure 3.1; blue colors, Table 3.3). These are results from analysis with a cluster threshold correction for multiple comparisons; an FWE correction for multiple comparisons resulted in clusters of greater activation for words than non-words primarily localized to temporo-parietal junction bilaterally and in a smaller cluster of greater activation for non-words than words in the left frontal lobe.

*Table 3.2*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in the contrast of verbs over non-words (voxelwise $p < .001$; cluster size > 27).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Supramarginal gyrus | Middle temporal gyrus, superior temporal gyrus, inferior parietal lobule, angular gyrus, | -57 | -46 | 34 | 1202 | 8.46 |
| L | Middle temporal gyrus | - | -54 | -7 | -23 | 255 | 5.27 |
| L | Middle frontal gyrus | - | -33 | 32 | 37 | 149 | 4.95 |
| L | Caudate nucleus | - | -9 | 5 | 1 | 77 | 4.70 |
| L | Cerebellum | - | -30 | -55 | -29 | 143 | 4.51 |
| L | Insula | - | -39 | 11 | -5 | 82 | 4.18 |
| L, R | Right supramarginal gyrus | Right middle temporal gyrus, right superior temporal gyrus, left and right precuneus, left and right middle cingulate cortex, left posterior cingulate cortex, right supplementary motor area, right precentral gyrus, right insula, right postcentral gyrus, right inferior parietal lobule, right superior frontal gyrus, right middle frontal gyrus, pars opercularis and pars orbitalis of right inferior frontal gyrus, right rolandic operculum | 51 | -40 | 25 | 3510 | 7.52 |
| L, R | Right lingual gyrus | Left and right calcarine gyrus, left lingual gyrus, left and right cuneus, left and right superior occipital gyrus, left middle occipital gyrus, left and right cerebellum | 15 | -76 | -11 | 1012 | 6.32 |
| R | Caudate nucleus | Thalamus | 9 | 8 | 4 | 201 | 5.27 |
| R | Middle frontal gyrus | - | 30 | 44 | 22 | 160 | 4.78 |
| R | Postcentral gyrus | - | 36 | -49 | 61 | 27 | 4.19 |

*Table 3.3*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in the contrast of non-words over verbs (voxelwise $p < .001$; cluster size > 27).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Pars opercularis of inferior frontal gyrus | Precentral gyrus | -42 | 5 | 22 | 116 | 5.62 |
| R | Hippocampus | - | 27 | -40 | 7 | 30 | 4.11 |

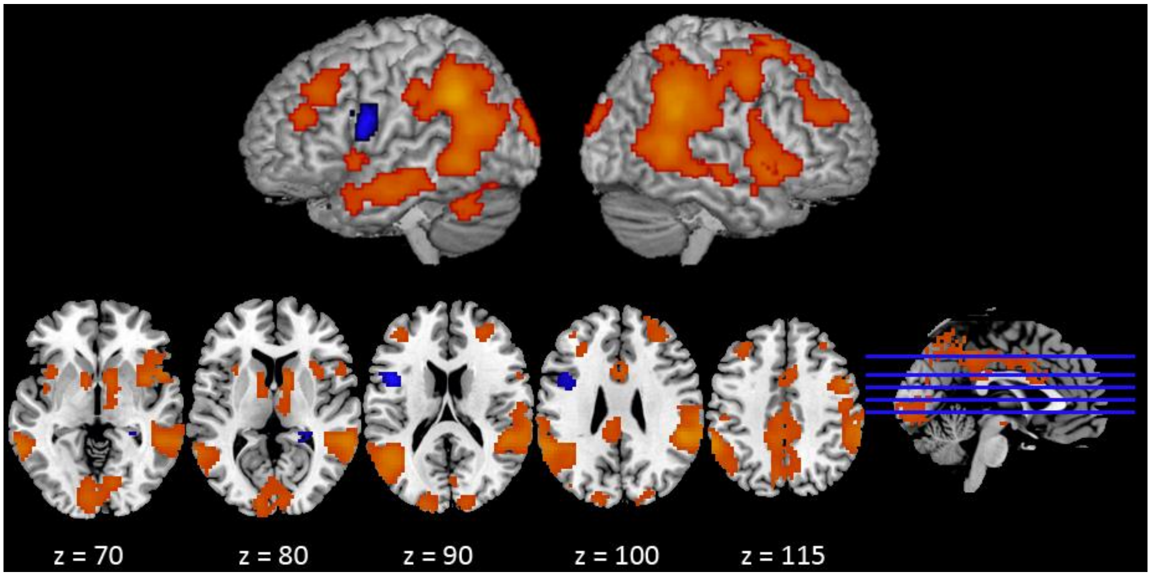


*Figure 3.1*. Brain areas showing increased activation for verbs than non-words (red colors) and for non-words than words (blue colors) (voxelwise $p < .001$; cluster size > 27).

*3.2.2.2. Number of subcategorization options*

The paired t-test analysis of *complete*-verbs vs. *demand*-verbs did not detect any clusters of increased activation associated with a greater number of subcategorization options (i.e., greater activation for *demand*-verbs than *complete*-verbs). The opposite contrast found clusters of increased activation associated with a lower number of subcategorization options (i.e., greater activation for *complete*-verbs than *demand*-verbs), mainly in bilateral frontal and occipital lobes, as well as in the left parietal lobe (Figure 3.2). A full list of activation clusters is presented in Table 3.3. These are results from analysis with a cluster threshold correction for multiple comparisons; an FWE correction for multiple comparisons resulted in very small clusters of activation in left insula, left occipital lobe and right fusiform gyrus.

*Figure 3.2*. Brain areas showing increased activation associated with a lower number of subcategorization options (*complete*-verbs > *demand*-verbs) (voxelwise $p < .001$; cluster size > 27)

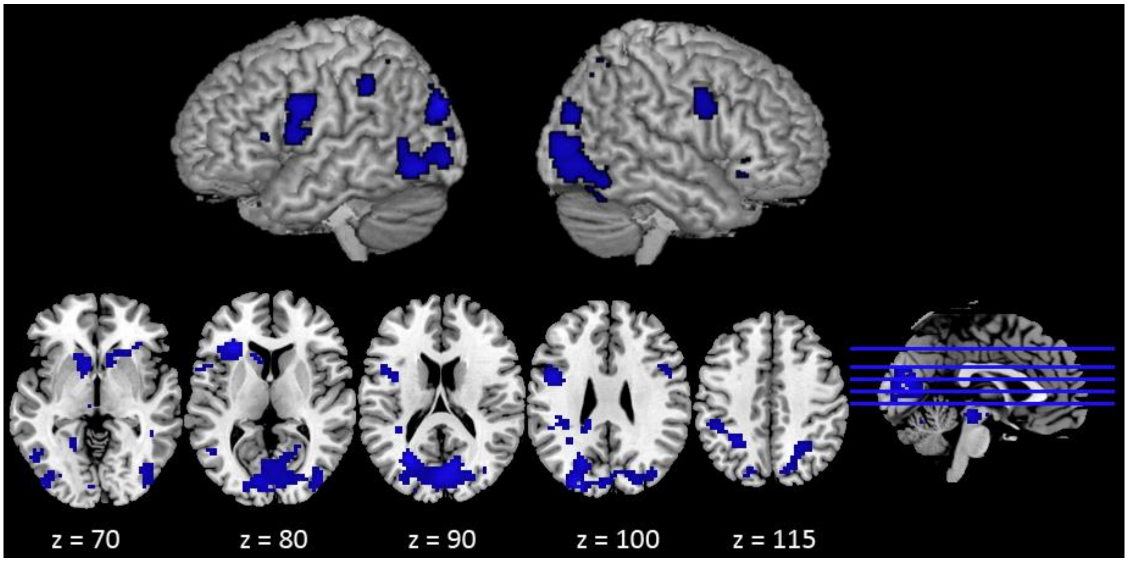


*Table 3.4*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in activation clusters associated with a lower number of subcategorization options (*complete*-verbs > *demand*-verbs) (voxelwise $p < .001$; cluster size > 27).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Insula | Pars opercularis of inferior frontal gyrus | -30 | 26 | 10 | 91 | 5.72 |
| L | Precentral gyrus | Pars opercularis of inferior frontal gyrus | -45 | 2 | 28 | 196 | 4.66 |
| L | Inferior parietal lobule | Superior parietal lobule | -27 | -52 | 40 | 281 | 4.60 |
| L | Inferior occipital gyrus | Inferior temporal gyrus, middle temporal gyrus, fusiform gyrus, lingual gyrus | -54 | -70 | -11 | 170 | 4.53 |
| L | Caudate nucleus | - | -9 | 17 | 4 | 121 | 4.40 |
| L | Middle occipital gyrus | - | -42 | -88 | -5 | 44 | 4.23 |
| L, R | Left superior occipital gyrus | Left and right calcarine gyrus, right fusiform gyrus, right superior occipital gyrus, right inferior occipital gyrus, left and right middle occipital gyrus, left and right cuneus, left and right lingual gyrus, right precuneus, right superior parietal lobule, right inferior temporal gyrus, right cerebellum | -27 | -64 | 19 | 2096 | 5.66 |
| R | Putamen | Caudate nucleus | 24 | 23 | -5 | 107 | 5.00 |
| R | Precentral gyrus | - | 51 | 5 | 31 | 38 | 3.71 |

*3.2.2.3. Number of thematic options*

The paired t-test analysis of *break*-verbs vs. *sing*-verbs did not find any increased activation associated with a greater number of thematic options (i.e., greater activation for *break*-verbs than *sing*-verbs). The opposite contrast found clusters of increased activation associated with a lower number of thematic options (i.e., greater activation for *sing*-verbs than *break*-verbs) in the left posterior and mid-anterior middle temporal gyrus and insula (Figure 3.3). A full list of activation clusters is presented in Table 3.4. These are results from analysis with a cluster threshold correction for multiple comparisons; no voxels survived an FWE correction for multiple comparisons.

*Table 3.5*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in activation clusters associated with a lower number of thematic options (*sing*-verbs > *break*-verbs) (voxelwise $p < .001$; cluster size > 27).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Middle temporal gyrus | - | -57 | -4 | -23 | 47 | 5.10 |
| L | Insula | - | -24 | 14 | -20 | 42 | 4.45 |
| L | Middle temporal gyrus | - | -54 | -46 | -8 | 29 | 3.73 |

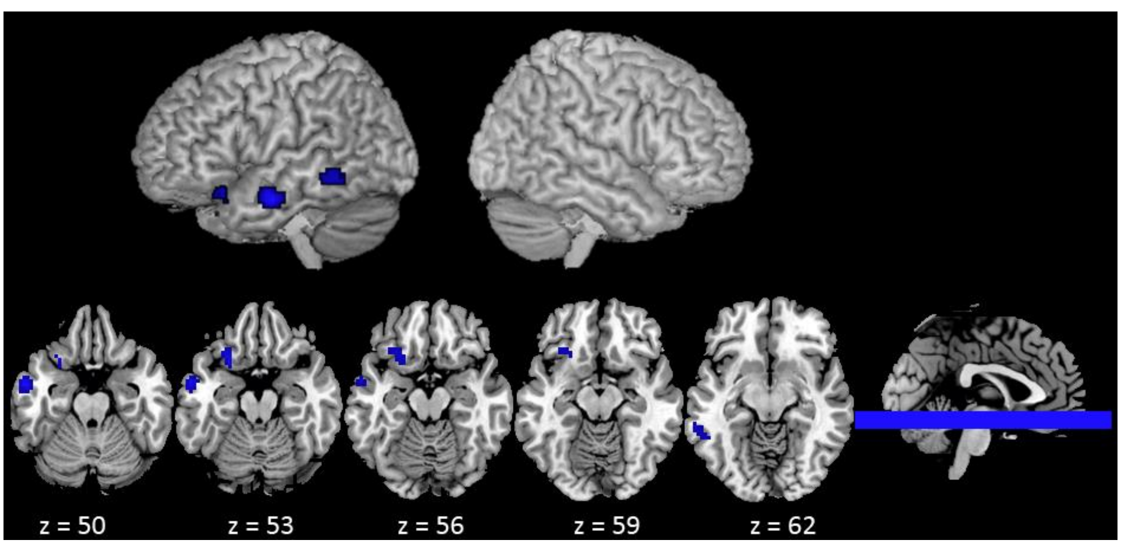


*Figure 3.3*. Brain areas showing increased activation associated with a lower number of thematic options (*sing*-verbs > *break*-verbs) (voxelwise $p < .001$; cluster size > 27).

*3.2.2.4. Number of number-of-argument options*

The paired t-test analysis of *sing*-verbs vs. *complete*-verbs found increased activation associated with a greater number of number-of-argument options (i.e., greater activation for *sing*-verbs than *complete*-verbs) in the left mid-anterior middle temporal gyrus (Figure 3.4, red colors). The opposite contrast found increased activation associated with a lower number of number-of-argument options (i.e., greater activation for *complete*-verbs than *sing*-verbs) in the white matter underlying right middle temporal gyrus, as well as in the right-hemisphere caudate nucleus and cerebellum (Figure 8, blue colors). A full list of activation clusters is presented in Tables 3.5 and 3.6. These are results from analysis with a cluster threshold correction for multiple comparisons; no voxels survived an FWE correction for multiple comparisons.

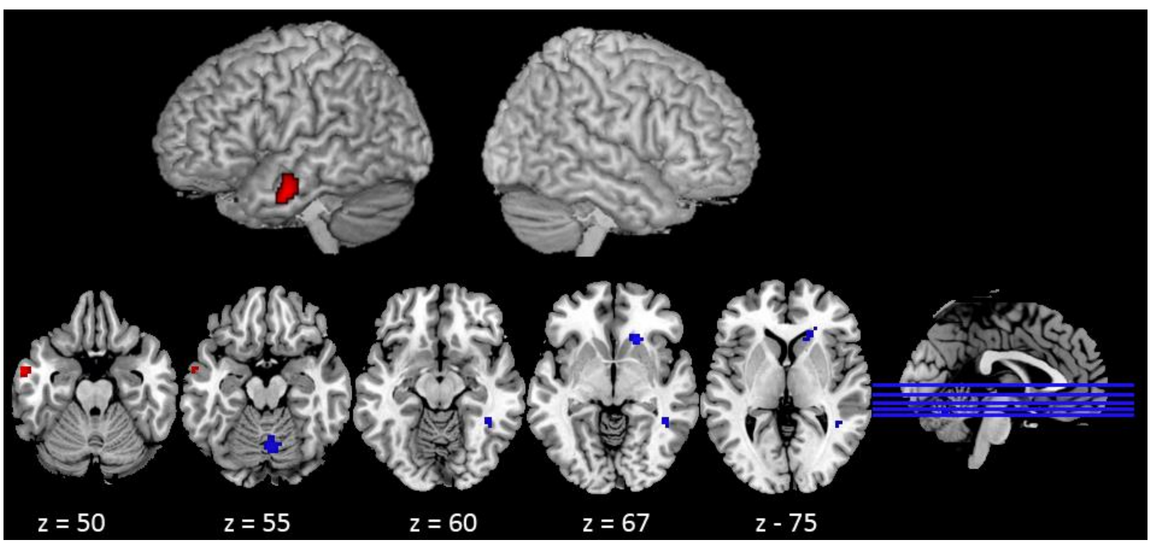


*Figure 3.4*. Brain areas showing increased activation associated with a greater number of number-of-argument options (*sing*-verbs > *complete*-verbs; red colors) and with a lower number of number-of-argument options (*complete*-verbs > *sing*-verbs; blue colors) (voxelwise $p < .001$; cluster size > 27).

*Table 3.6*. AAL regions, MNI coordinates, cluster size and maximal *t*-values for local maxima in activation clusters associated with a greater number of number-of-argument options (*sing*-verbs > *complete*-verbs) (voxelwise *p* < .001; cluster size > 27).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| L | Middle temporal gyrus | - | -57 | -1 | -29 | 37 | 4.66 |

*Table 3.7*. AAL regions, MNI coordinates, cluster size and maximal t-values for local maxima in activation clusters associated with a lower number of number-of-argument options (*complete*-verbs > *sing*-verbs) (voxelwise p < .001; cluster size > 27).

| Left/ Right | Activation peak | Cluster extent | *x* | *y* | *z* | Cluster size | *t*-Max |
|---|---|---|---|---|---|---|---|
| R | White matter underlying middle temporal gyrus[9] | - | 45 | -46 | -2 | 4.77 | 32 |
| R | Caudate nucleus | - | 21 | 23 | -5 | 4.73 | 39 |
| R | Cerebellum | - | 6 | -67 | -17 | 4.13 | 34 |

*ROI analysis*

Mean percent signal change in the four verb conditions in the seven regions-of-interest are presented in Figure 3.5.

[9] Since automated labeling found a large part of the cluster to lie outside the gray-matter areas included in the atlas, judgment of their location was based on visually reviewing the activation.

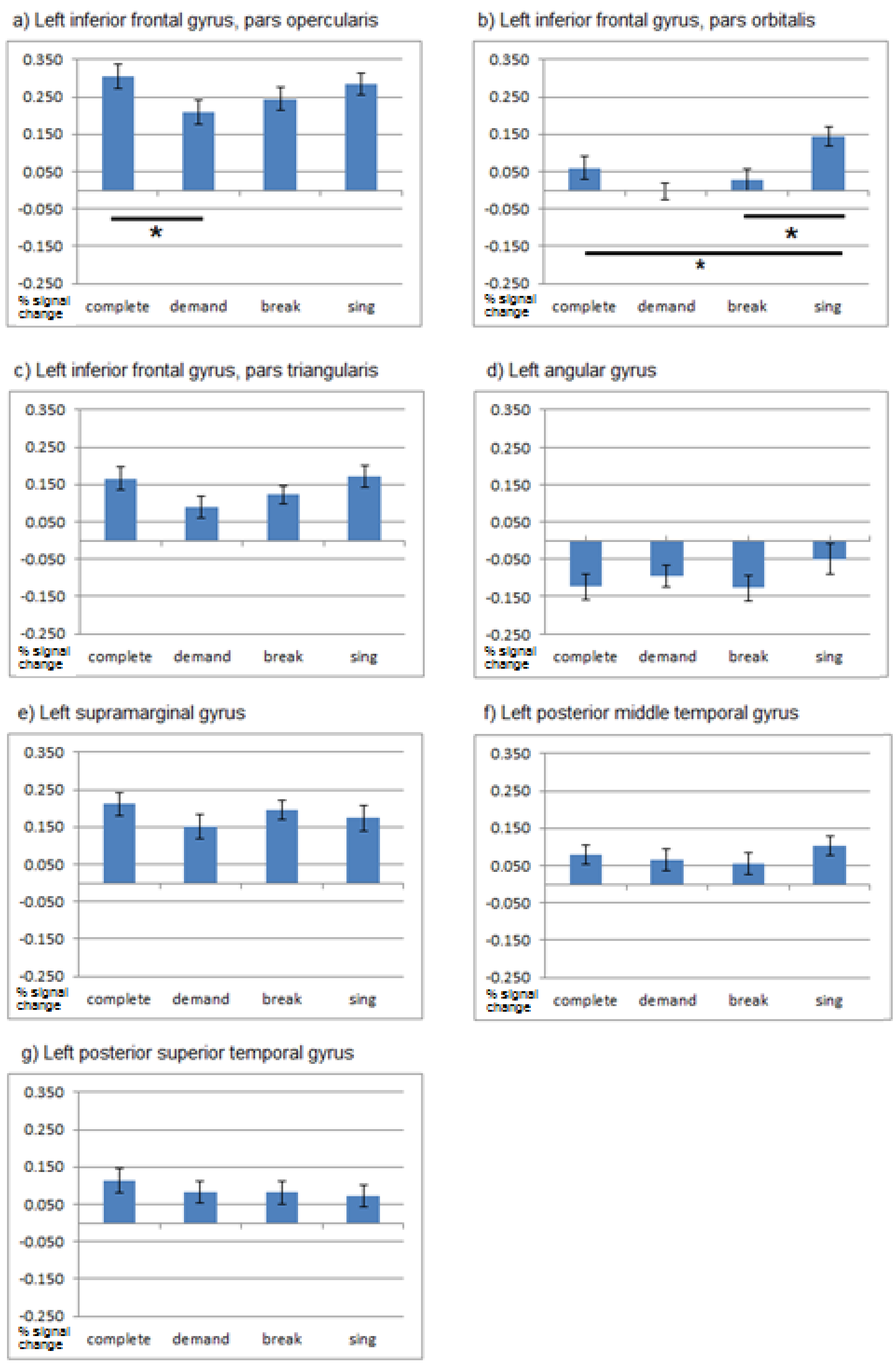


*Figure 3.5.* Mean percent signal change in the four verb conditions in the seven regions-of-interest in Experiment 2. Error bars indicate the standard error of the mean. * indicates a priori planned pairwise comparisons that were significant after Bonferroni correction for multiple comparisons ($p < .017$).

Repeated-measures ANOVAs found significant effects of verb condition in pars opercularis of the left inferior frontal gyrus ($F(3,60) = 4.41$, $p = .007$) and pars orbitalis of the left inferior frontal gyrus ($F(3,60) = 8.32$, $p < .001$). For pars opercularis of the left inferior frontal gyrus, follow-up pairwise comparisons revealed a greater percent signal change associated with a smaller number of subcategorization options, i. e., in *complete*-verbs compared to *demand*-verbs ($p = .005$). For pars orbitalis of the left inferior frontal gyrus, follow-up pairwise comparisons revealed a greater percent signal change associated with a smaller number of thematic options, i.e., in *sing*-verbs compared to *break*-verbs ($p = .004$), and with a greater number of number-of-argument options, i. e., in *sing*-verbs compared to *complete*-verbs ($p = .009$). The effect of verb condition was not significant in the other five regions of interest (pars triangularis of the left inferior frontal gyrus, left supramarginal gyrus, left angular gyrus, left posterior middle temporal gyrus, left posterior superior temporal gyrus).

### 3.3. Discussion

Experiment 2 used fMRI to investigate the neural correlates of three understudied VAS characteristics (number of subcategorization options, number of thematic options and the overall number of number-of-argument options) in a single-word-level processing task. The validity of the experiment is confirmed by high performance of healthy participants. Since the experiment used a standard lexical decision task, its validity is further supported by an expected pattern of results in the contrast of words versus non-words. Words elicited increased activation relative to non-words in an extensive bilateral network of areas in the frontal lobe, temporal lobe and temporo-parietal junction, which is highly similar to results of previous studies using the same task (e.g., Fiebach, Friederici & von Cramon, 2011; Grindrod, Garnett, Malyutina and Den Ouden, 2014).

To summarize the results of Experiment 2, areas of increased activation for more complex verbs were found for only one out of three investigated VAS characteristics (number of number-of-argument options, but not number of subcategorization options or number of thematic options). Unexpectedly, for all three investigated VAS characteristics, the analysis found areas of increased activation for less complex verbs. The findings for each VAS characteristic are discussed in more detail below, followed by an overall discussion of neuroimaging Experiments 1 and 2 (Section 3.4).

*3.3.1. Number of subcategorization options*

A greater number of number-of-argument options was not associated with increased activation in any brain areas in either whole-brain or ROI analysis. To the best of our knowledge, this was the first study of subcategorization options in a single-word-level task; thus, no data from previous literature are available for comparison. Relative to the hypothesis (verbs with a greater number of subcategorization options being more complex and thus requiring a greater neural involvement), the results were in the opposite-to-hypothesized direction. This suggests that in a single-word-level task, unlike in a sentence-level task, not all subcategorization options of the verb are exhaustively accessed, possibly because there is no need for prediction of the upcoming verb complement. Thus, no additional activation is observed for verbs with a greater number of subcategorization options.

A lower number of subcategorization options was associated with increased activation in the frontal and occipital lobe bilaterally, as well as in the left parietal lobe in the whole-brain analysis; the ROI analysis revealed increased activation in one ROI categorized as associated with semantic integration (pars opercularis of the left inferior frontal gyrus). The result was robust, with part of activation surviving an FWE correction for multiple comparisons. One possible account for this activation is that even though a greater number of subcategorization options places an additional processing load when all of the options are accessed, it may at the same time "strengthen" verb representations and make them more "robust" or provide them with additional access routes by means of building more connections in the mental lexicon, facilitating lexical access under processing conditions such as in the single-word-level context, when not all of associated information needs to be fully activated. On the other hand, representations of verbs with a lower number of subcategorization options may lack these beneficial connections and thus be more difficult to access, leading to increased brain activation in single-word processing. This account is also supported by behavioral findings of the present experiment: a lower number of subcategorization options was associated with slower reaction times, suggesting a greater difficulty in lexical access. However, the question still remains as to why the specific brain areas showing increased activation levels for access to less complex verbs (left inferior parietal lobule and left frontal areas, including pars opercularis of left inferior frontal gyrus) are those more likely associated with semantic integration, rather than semantic storage and retrieval. Integration does not seem relevant to a single-word-level task, so the activation of these areas may reflect some of their other functions in sub-processes of word form processing or lexical retrieval. For example, Heim, Eickhoff, Friederici & Amunts (2009) argue for the involvement of pars opercularis of the left inferior frontal gyrus in selection processes during lexical retrieval.

Also, within the present experiment, pars opercularis of the left inferior frontal gyrus showed increased activation for non-words relative to all verbs, which provides additional evidence of it being involved in other functions in addition to semantic/syntactic integration.

*3.3.2. Number of thematic options*

The analysis did not find any brain areas of increased activation for verbs with a greater number of thematic options in either whole-brain or ROI analysis. Relative to the hypothesis (verbs with a greater number of thematic options eliciting greater neural activation, since more linguistic information is accessed), the result was in the opposite direction. It suggests that thematic options of the verb may not be exhaustively accessed in the lexical decision task, where processing conditions do not point to a particular thematic option of the verb or require the language comprehender to select one.

A lower number of thematic options was associated with increased activation in left mid-anterior and posterior middle temporal gyrus and insula in the whole-brain analysis; the ROI analysis revealed increased activation in one ROI categorized as associated with semantic storage/retrieval (pars orbitalis of the left inferior frontal gyrus). This indicates an additional processing load associated with verbs that have a lower number of thematic options. This is inconsistent with the results of previous single-word-level experiments (Meltzer-Asscher et al., 2012, 2015) that found areas of increased activation (left inferior frontal gyrus in Meltzer-Asscher, 2015; a bilateral network of parietal, posterior temporal and middle and superior frontal regions in Meltzer-Asscher et al., 2012) for verbs with a greater, but not lower, number of thematic options. A possible account for inconsistency is that the design of the present study and previous studies may not be comparable: Meltzer-Asscher et al. (2012, 2015) did not manipulate the number of thematic options independently of the number of number-of-argument frames, which may have introduced a confound, absent in the present study.

The results of the present single-word experiment may possibly be interpreted in the same way as the similar pattern for subcategorization options, discussed above. It is possible that in a single-word-level task, unlike in a sentence-level task, not all thematic options of the verb are exhaustively accessed, possibly because there is no need for sentence integration – only superficial word form recognition is required. Thus, no additional activation is observed for verbs with a greater number of thematic options. As in the case of subcategorization options, the question remains as to what causes additional activation associated with processing verbs with a lower number of thematic options. One possibility is that a greater number of thematic options may actually make a verb representation more "robust" or "rich" by means of building more connections in the mental lexicon, thus actually facilitating lexical access under processing conditions such as in the single-word-level context, when not all of associated information needs to be fully activated (see more detailed discussion above, in the section dedicated to subcategorization options). The location of activation areas (left posterior and mid-anterior middle temporal gyrus and insula in the whole brain analysis; pars orbitalis of left inferior frontal gyrus in the ROI analysis) suggests that the nature of increased load more likely pertains to semantic storage/retrieval rather than to integration, which is consistent with our suggestion about more difficult semantic access to less "robust" representations of verbs with a lower number of thematic options under single-word processing conditions.

*3.3.3. Number of number-of-argument options*

A greater number of number-of-argument options was associated with increased activation in left mid-anterior middle temporal gyrus in the whole-brain analysis, as well as in pars orbitalis of left inferior frontal gyrus, as revealed by the ROI analysis. These results go in the hypothesized direction and point to an additional processing load associated with a greater number of number-of-argument options. Specific activated brain areas indicate that the nature of the load more likely pertains to semantic storage/retrieval than to integration, which is consistent with what processes are expected to be involved in a single-word-level task. Verbs with a greater number of number-of-argument options are associated with a greater amount of information with regard to VAS frames that they can be used in, and access to these verbs in single-word-level processing may involve exhaustive retrieval of this information. Even though this result was in the hypothesized direction, it was not consistent with an earlier single-word-level experiment by Meltzer-Asscher et al. (2015), who did not find any areas of increased activation for verbs with a greater number of number-of-argument options. However, they used a different type of contrast, comparing "alternating" verbs (i.e., verbs with multiple number-of-argument options) to both one-argument and two-argument verbs with one number-of-argument option, whereas our analysis only included two-argument verbs with one number-of-argument option. This difference in design, leading to a qualitative difference in the performed comparisons, may have contributed to conflicting results.

A lower number of number-of-argument options was associated with increased activation of white matter underlying right middle temporal gyrus, as well as in the right-hemisphere caudate nucleus and cerebellum in the whole-brain analysis; the ROI analysis did not reveal any areas of greater activation. This was not an expected result, neither was it consistent with Meltzer-Asscher et al. (2015), who did not find any areas of increased activation for verbs with a lower number of number-of-argument options. As in the case of similar patterns reported above for the other two investigated VAS characteristics (areas of greater activation for lower complexity verbs), one may speculate that a smaller amount of information and connections in the mental lexicon for lower-complexity verbs may make their representations less "robust" / "rich" and thus more difficult to access under some processing conditions.

### 3.4. Overall discussion of neuroimaging experiments

The two neuroimaging experiments used the same experimental design to investigate the neural correlates of several VAS characteristics in two processing conditions: sentence processing (Experiment 1) and single-word processing (Experiment 2). The validity of both experiments is confirmed by high performance (accuracy), which was expected of healthy participants in our experimental tasks. The validity of Experiment 2 is further supported by an expected pattern of results in the words versus non-words contrast in the lexical decision task. Results of Experiments 1 and 2 are summarized in Tables 3.7 (whole-brain analyses) and 3.8 (ROI analysis).

*Table 3.8*. Summary of results of whole-brain analyses of Experiments 1 and 2: Brain areas showing increased activation in performed statistical comparisons.

| *VAS characteristic* | *Direction of comparison* | *Experiment 1 (sentence level)* | *Experiment 2 (single-word level)* |
|---|---|---|---|
| Number of subcategorization options | More > less complex verbs | L superior frontal gyrus, posterior middle temporal gyrus, angular gyrus | n/s |
| | Less > more complex verbs | n/s | L and R frontal and occipital regions; L parietal lobe |
| Number of thematic options | More > less complex verbs | L cingulum, white matter underlying L inferior frontal gyrus | n/s |
| | Less > more complex verbs | R angular gyrus | L posterior and mid-anterior middle temporal gyrus and insula |
| Number of number-of-argument options | More > less complex verbs | n/s | L mid-anterior middle temporal gyrus |
| | Less > more complex verbs | L superior frontal gyrus | R middle temporal gyrus, caudate nucleus and cerebellum |

L – left; R – right

*Table 3.9*. Summary of results of ROI analyses of Experiments 1 and 2.

| *ROI group* | *ROI* | *Experiment 1(sentence level)* | *Experiment 2 (single-word level)* |
|---|---|---|---|
| Syntactic / semantic integration | Pars triangularis of LIFG | - | - |
| | Pars opercularis of LIFG | - | ↑ for a lower number of subcategorization options |
| Semantic storage / retrieval | Pars orbitalis of LIFG | - | ↑ for a greater number of number-of-argument options<br>↑ for a lower number of thematic options |
| | LpMTG | ↑ for a greater number of subcategorization options | - |
| | LpSTG | - | - |
| | L angular gyrus | - | - |
| | L supramarginal gyrus | - | - |

LIFG – left inferior frontal gyrus; LpMTG – left posterior middle temporal gyrus; LpSTG – left posterior superior temporal gyrus. ↑ - increased activation. The table includes results of planned pairwise comparisons that were significant after Bonferroni correction for multiple comparisons with an overall $\alpha < .05$.

Results for all three investigated VAS characteristics differed depending on processing conditions, i.e., in sentence-level processing (Experiment 1) and single-word-level processing (Experiment 2). For the number of subcategorization options and the number of semantic options, the observed pattern was similar. Namely, in sentence-level processing there were areas of increased activation for verbs of greater complexity (i.e., verbs with a greater number of subcategorization/thematic options) but not for verbs of lower complexity (with an exception of right angular gyrus activation for a lower number of thematic options). On the other hand, in single-word-level processing, there were areas of increased activation for verbs of lower complexity (i.e., verbs with a lower number of subcategorization/thematic options) but not for verbs of greater complexity.

This pattern indicates that both the number of subcategorization options and thematic options affect verb processing, modulating the amount of neural resources needed for it. However, it depends on the task whether the effect of greater linguistic complexity is facilitatory or detrimental. It is possible that a greater number of VAS options may actually "strengthen" verb representations and make them more "robust" by means of building more connections in the mental lexicon (similar to effects of semantic neighborhood density, e.g., Buchanan, Westbury & Burgess, 2001; Shaoul & Westbury, 2010). This may actually facilitate lexical access under processing conditions such as in the single-word-level context, when not all of associated information needs to be fully activated, while representations of verbs with a lower number of VAS options may lack these beneficial connections and thus be more difficult to access, leading to increased brain activation in single-word processing. This account is further supported by behavioral results of the present experiment that preliminarily indicate that a lower number of VAS options may be associated with poorer behavioral performance (slower reaction times associated with a lower number of subcategorization options and lower accuracy associated with a lower number of thematic options).

On the other hand, in sentence-level processing, additional information associated with verbs with a greater number of VAS options may need to be retrieved to a fuller extent for the purposes of efficient sentence comprehension (e.g., in order to engage in prediction of the complement that follows the verb (Kamide, 2008)). This full retrieval of

VAS information may require additional neural resources. For the number of subcategorization options, this additional activation is localized mainly in left-hemisphere posterior (temporal and temporo-parietal) regions, which is partially consistent with previous findings by Shetreet et al. (2007, 2010) (in that left posterior brain areas are involved; however, not in terms of specific brain areas) and possibly indicates that additional resources are used for retrieval of additional information in the mental lexicon. No increased activation is seen in hypothesized "integration areas", which may imply that even though multiple subcategorization options are retrieved, no attempt is made to integrate them into a sentence, where a particular subcategorization option is already selected by context. In contrast, for the number of thematic options additional activation is localized in anterior brain areas, possibly indicating that an additional processing load may have to do with selecting an appropriate VAS option out of multiple options and integrating it into sentence context, rather than with VAS access per se.

However, the pattern was different for the third VAS characteristic, the number of number-of-argument options. For this characteristic, the sentence-level task revealed areas of greater activation for lower complexity verbs (in the left superior frontal gyrus), but not for greater complexity verbs. The single-word level task revealed areas of greater activation both for greater complexity verbs (in the left mid-anterior middle temporal gyrus) and lower complexity verbs (in white matter underlying right middle temporal gyrus, in caudate nucleus and cerebellum).

Among the three investigated VAS characteristics, the number of number-of-argument options was the only one that showed increased activation for lower complexity verbs both in sentence-level processing and in single-word-level processing. However, the location of activations was different: in sentence-level processing it was left mid-anterior middle temporal gyrus, whereas in single-word-level processing it was white matter underlying right middle temporal gyrus, caudate nucleus and cerebellum. This may indicate that even though less "robust" lexical representations of verbs with a lower number of number-of-argument options may place an additional load under both processing conditions, the specific processes that become more difficult may not be exactly the same in sentence-level and single-word-level processing. Overall, all the regions showing increased activation for less complex verbs in either task likely reflect higher demands for general attentional and/or executive processing. For example, at single-word level, increased activation of the left superior frontal gyrus may reflect mental manipulation and monitoring of information (e.g., du Boisgueheneuc, 2006); at the sentence level, activation of right temporal gyrus may possibly reflect selective attention (Sörös et al., 2007), while caudate nucleus may be involved in goal-directed action (Grahn, Parkinson & Owen, 2008) and cerebellum may reflect manipulation of information (cerebellum, Schmahmann & Caplan, 2006). Thus, while it does not yet seem possible to be more specific about how these processes differ between single-word-level and sentence-level processing, the findings overall indicate that verbs with a lower number of number-of-argument options present a greater cognitive difficulty at some levels of processing.

However, all clusters of activation associated with the number of number-of-argment options were of very small volume and none of them survived an FWE correction for multiple comparisons. One should note that previous findings on the number of number-of-argument options are not very robust either, with two studies failing to find any significant activations (Shetreet et al., 2010, Meltzer-Asscher et al., 2015; see, however, parametric analysis in Shetreet et al., 2007). Taken together, the evidence may suggest that the number of number-of-argument options may not produce any robust effects, which may indicate that this characteristic is possibly not stored as part of lexical entry of verbs.

The number of number-of-argument options may be the most “syntactic” among the VAS characteristics investigated here. In other words, the other two investigated VAS characteristics may be associated with particular properties of the verbs’ meanings. For instance, verbs with a greater number of subcategorization options have in common the fact that their semantics allows complementation by a proposition (a vast theoretical linguistic literature discusses semantic properties of such verbs: e.g., Rudanko, 1996). For verbs with a greater number of thematic options, the common semantic property is that they typically describe a change of state (Wright, 2002; Chierchia, 2003). Even though experimental groups were matched for imageability as a crucial semantic parameter, they still retain these inherent semantic differences. However, there do not seem to be such salient semantic differences between verbs with a greater versus lower number of number-of-argument options. Based on this, one may speculate that the neural effects of the number of subcategorization options and thematic options may actually be mediated by accessing and selecting/integrating semantic information associated with these verbs, rather than a separate grammatical component of their lexical entries that contains VAS information. This speculation may be further supported by the fact that greater activation for verbs with a greater number of subcategorization/thematic options was observed in the sentence-level task, which requires deep semantic processing, but not in the lexical decision that only requires superficial access to lexical knowledge about the verb.

Thus, taken together, our findings may actually indicate that an additional load in the processing of verbs with a greater number of subcategorization and thematic options (as well as with a greater number of arguments, which was not part of our experiments but has been the focus of many previous studies) may largely be mediated by inherent semantic properties of such verbs, rather than by automated exhaustive access to purely grammatical VAS information.

Lastly, it is notable that the general brain region that was most frequently activated across contrasts was the left middle temporal gyrus. Its posterior portion showed increased activation for a greater number of subcategorization options in sentence-level processing and a lower number of thematic options in single-word-level processing. The mid-anterior portion of the left middle temporal gyrus showed increased activation for a lower number of thematic options in single-word-level processing and for a greater number of number-of-argument options in sentence processing. The activation in left middle temporal gyrus has also been observed in previous research (posterior portion activated for the number of arguments (Den Ouden et al., 2009), mid-anterior and posterior portions activated for the number of subcategorization options (Shetreet et al., 2010)). Thus, it appears that even though previous literature has largely emphasized the role of the left temporo-parietal junction and, perhaps to a lesser extent, left inferior frontal regions in VAS processing (Thompson et al., 2013; Thompson & Meltzer-Asscher, 2014), mid-anterior and posterior portions of the left posterior middle temporal gyrus may also be vastly involved in VAS processing. Previous neuroimaging studies of language have extensively shown the involvement of both posterior and mid-anterior portions of left middle temporal gyrus in lexical-semantic retrieval (posterior portion: Bedny et al., 2008; Gold et al., 2006; Noppeney, Phillips, & Price, 2004; Krieger-Redwood & Jefferies, 2014; anterior portion: Patterson et al., 2007; Schwartz et al., 2009; Walker et al., 2011), although the role of the anterior portion of middle temporal gyrus is more controversial and is often also associated with complex syntactic processing (Humphries et al., 2005; Caplan et al., 2008; Magnusdottir et al., 2013).

Although the neuroimaging results discussed above provide an important insight into neural effects of VAS complexity, any conclusions and interpretations remain tentative without knowing the behavioral effects of these characteristics. For example, throughout all discussion above, a greater neural activation was interpreted as a sign of a greater processing load. However, it could alternatively be interpreted in a less traditional way: as a sign of more robust and temporally focused processing, leading to temporally uniform and easier detectable activation. Testing of behavioral effects can help to test this alternative account. If conditions associated with a greater neural activation also show better behavioral performance, this would prove the alternative interpretation of the greater neural activation being due to more robust and less temporally "noisy" processing (i.e., with less temporal variance). If conditions associated with a greater neural activation show poorer behavioral performance, this would go against the alternative interpretation and support the more traditional interpretation of greater neural activation as a sign of a greater processing load. Behavioral data from Experiment 2 preliminarily indicate that this is the case and that a greater neural activation is a sign of a greater processing load, at least in a single-word-level task. Experiment 3 will test behavioral effects of the three investigated VAS characteristics in both single-word-level and sentence-level processing conditions.

# CHAPTER 4

## EXPERIMENT 3: BEHAVIORAL EFFECTS OF VAS PROCESSING IN A SINGLE-WORD-LEVEL AND SENTENCE-LEVEL TASK

Experiment 3 was a behavioral experiment that aimed to investigate VAS effects on processing speed and accuracy of healthy speakers under two different processing conditions: at the sentence and single-word processing level. Sentence-level neuroimaging Experiment 1 did not include an overt response to experimental trials in order not to "overshadow" any condition-related brain activity by response-related brain activity; thus, it could only provide data on accuracy, but not on processing speed. Experiment 3 aims to fill this caveat. Single-word-level neuroimaging Experiment 2 did collect data on both accuracy and processing speed. However, Experiment 3 can indicate whether the effects are robust (i.e., whether the findings will be replicated). An additional strength of Experiment 3 is that both tasks are tested in the same participants; thus, any modulation of VAS effects by task cannot be ascribed to individual between-participant differences in language processing and have to be accounted for by task factors.

Investigating behavioral effects of VAS characteristics is important for conclusive interpretation of their neural effects. Throughout all discussion of neural effects above, a greater neural activation was interpreted as a sign of a greater processing load. However, it could alternatively be interpreted in a less traditional way: as a sign of more robust and temporally focused processing, leading to temporally uniform and easier detectable activation. Testing of behavioral effects can help to test this alternative account. If conditions associated with a greater neural activation also show better behavioral performance, this would prove the alternative interpretation of the greater neural activation being due to more robust and less temporally ‘fuzzy’ processing. If conditions associated with a greater neural activation show poorer behavioral performance, this would go against the alternative interpretation and support the more traditional interpretation of greater neural activation as a sign of a greater processing load. It was hypothesized that this would be the case: i.e., a greater number of subcategorization options and thematic options would be associated with poorer behavioral performance in a sentence-level task and better behavioral performance in a single-word-level task. No behavioral effects were expected for the number of number-of-argument options, since this characteristic does not seem to elicit any reliable neural effects.

## 4.1. Method

### *4.1.1. Participants*

20 neurologically healthy young participants participated in the study (14 females; mean age 22.4, SD 3.2, range 19-30 years; mean number of years of formal education 15.7, SD 1.7, range 13-19). All participants were right-handed, native speakers of English and did not have a reported history of neurological or speech, language, hearing and reading disorders. Participants had normal or corrected-to-normal vision. Participants received either monetary compensation or extra course credit if applicable. None of the participants had participated in Experiments 1 or 2, which included the same stimuli as Experiment 3.

*4.1.2. Design*

The study design was identical to the design of Experiments 1 and 2 and included the same four experimental groups of verbs, allowing to perform the same contrasts (please refer to Section 2.1.2).

*4.1.3. Tasks*

The single-word level lexical decision task was identical to the task in Experiment 2. Participants were instructed to press one button on the keyboard if they saw a string of letters that made a real English word (e.g., "*to break*") and a different button if a string of letters was not a real word of English (e.g., "*to crain*"). All words and non-words were preceded by "*to*" (e.g., "*to break*" rather than "*break*") to ensure their unambiguous interpretation as verbs. The experiment was self-paced, with items being presented for a maximum of 1.5 seconds with an inter-stimulus interval of 1.5 seconds. The order of presentation of individual stimuli was randomized for each participant. A fixation cross was presented in the center of the screen between the stimuli.

The sentence task was almost identical to the task in Experiment 1, the only difference being that in the present experiment participants always had to press a button to make a response. They silently read sentences presented in full (as opposed to word-by-word) and pressed one button on the keyboard if a sentence was a well-formed sentence of the English language or pressed a different button if a sentence was not well-formed, i.e., either was not grammatical ("syntactic fillers") or was not meaningful ("semantic fillers"). The experiment was self-paced, with sentences presented for a maximum of 3.0 seconds with an inter-stimulus interval of 2.0 seconds. The order of presentation of individual stimuli was randomized for each participant. A fixation cross was presented in the center of the screen between the stimuli.

*4.1.4. Stimuli*

For the lexical decision task, stimuli included 20 verbs in each group, for a total of 80 verbs (full list of verb stimuli along with a justification of their inclusion into experimental groups is presented in Appendix 1), plus 18 extra verbs included in order to pilot stimuli for Experiment 2 (Experiment 3 was conducted before Experiment 2, so if any verbs appeared to be "outliers" based on reaction times or accuracy in Experiment 3, they could be replaced by some of the "extra" verbs for Experiment 2), and 196 non-words (for a word to non-words ratio of 1:2). All stimuli were preceded by "*to*" (e.g., "*to break*" rather than "*break*") to ensure their unambiguous interpretation as verbs. Non-words were pronounceable and were formed by re-combining pronounceable segments of experimental verbs. Non-words were matched to verbs on length in syllables and letters and on the orthographic neighborhood size (Medler & Binder, 2005). Verb groups were matched for lexical frequency based on the CELEX database (Baayen et al., 1995), length in syllables and letters, imageability (as measured in the preliminary online survey, see Experiment 2 for details) and orthographic neighborhood size (Medler & Binder, 2005).

For the sentence task, experimental stimuli were sentences that included 20 verbs from each of the experimental groups, used twice each, for an overall of 160 sentences (full list of sentence stimuli is presented in Appendix 2; for justification of inclusion of verbs into experimental groups refer to Appendix 1). The stimuli were identical to those from Experiment 1, with an exception of 14 sentences (i. e., 7 verbs) that were changed in order to achieve better matching for imageability based on the preliminary online survey.

All sentences had the same structure and included a subject noun phrase, a verb predicate in the past tense and an object noun phrase (e.g., *The user completed the survey; The buyer demanded a refund*; etc.). Using the same sentence structure ensured that any behavioral effects can only be ascribed to VAS access rather than the processing of varying contexts. Sentences were matched across conditions on their overall length in the number of words and syllables, as well as on linguistic properties of verbs (lexical frequency based on the CELEX database (Baayen et al., 1995), length in syllables and letters, imageability as measured in the preliminary survey) and linguistic properties of object and subject nouns (lexical frequency based on the CELEX database (Baayen et al., 1995), imageability (Coltheart, 1981), number of singular/plural nouns, number of animate and inanimate nouns).

Additionally, since the task was to judge the well-formedness of sentences, the sentence task stimuli included 80 not-well-formed filler sentences. Forty of them ("syntactic fillers") were not-well-formed from the syntactic point of view, i.e., included an intransitive verb followed by a direct object (e.g., *The plan depended the weather, The group arrived the village*). The other 40 fillers ("semantic fillers") were not-well-formed from the semantic point of view, i.e., included words that do not form a meaningful combination (e.g., *The test adored the flaws; The landlord announced the skirt*). Two different types of fillers were used to make sure that participants attended to both grammar and meaning of the stimuli. Some of the verbs were repeated within fillers as well as across fillers and experimental sentences so that participants would not be able to strategically judge sentences based on whether they included a repeated verb, instead of attending to their content.

*4.1.5. Procedures*

Participants were seated in front of a laptop in a quiet room. They signed an informed consent form, were given instructions on the tasks and completed a practice set that did not include any of experimental items. The practice set contained 15 trials for the lexical decision task and 10 trials for the sentence task. All participants first completed the lexical decision task and then the sentence task, so that the presentation of verbs in isolation in the lexical decision task could not be affected by any memory traces of sentences. The lexical decision task took a maximum of 15 minutes, with additional time for two breaks of self-determined duration. Order of individual stimuli presentation was randomized for each participant. The sentence task took a maximum of 21 minutes, with additional time for three breaks of self-determined duration. Order of individual stimulus presentation was randomized for each participant. E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm) was used for stimulus presentation and recording of the responses.

*4.1.6. Data analysis*

Reaction times and accuracy were analyzed separately for the lexical decision task and the sentence task. Only correct responses were included into the analysis of reaction times. Accuracy values were log-transformed prior to statistical tests (Bartlett, 1947; Hoyle, 1973). The following a priori planned paired *t*-tests were performed: a test comparing *demand*-verbs vs. *complete*-verbs to investigate an effect of subcategorization options, a test comparing *complete*-verbs vs. *sing*-verbs to investigate an effect of the number of number-of-argument options, and a test comparing *sing*-verbs vs. *break*-verbs to investigate the number of thematic options. These were performed on average participants' accuracy and reaction times as paired t-tests in the SPSS 22 software (http://www-01.ibm.com/software/analytics/spss). For each outcome measure, Bonferroni correction for multiple comparisons was applied, resulting in $\alpha$ = .017 for an overall significance level of $\alpha$ = .05.

## 4.2. Results

### *4.2.1. Lexical decision task*

In the lexical decision task, the average accuracy was 96.5% (SD 2.9%, range 88.8 – 100.0%) and the average reaction time was 652 ms (SD 58 ms, range 662 – 797 ms). No participants had to be excluded from the analysis due to low performance. Average accuracy and reaction times in experimental conditions are presented in Table 4.1.

*Table 4.1*. Average accuracy and reaction time in the lexical decision task in Experiment 3, mean (SD).

| | *Complete*-verbs | *Demand*-verbs | *Sing*-verbs | *Break*-verbs | Non-words |
|---|---|---|---|---|---|
| Accuracy | 96.3 % (5.1 %) | 97.5% (5.5 %) | 94.8 % (5.3 %) | 97.5 % (3.0 %) | 95.7 % (2.5 %) |
| Reaction time | 666 ms (68 ms) | 634 ms (49 ms) | 670 ms (81 ms) | 640 ms (53 ms) | 689 ms (94 ms) |

The three Bonferroni-corrected planned paired *t*-tests on reaction times revealed that verbs with a greater number of subcategorization options (*demand*-verbs) had faster reaction times than verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = 3.52$, $p = .002$); verbs with a greater number of thematic options (*break*-

verbs) had faster reaction times than verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 2.82$, $p = .011$); no difference was found between verbs with a greater number of number-of-argument options (*sing*-verbs) and verbs with a lower number of number-of-argument options (*complete*-verbs) ($t(19) = .41$, $p = .68$).

The three Bonferroni-corrected planned paired *t*-tests on log-transformed accuracy revealed that there was no difference in accuracy between verbs with a greater number of subcategorization options (*demand*-verbs) and verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = -.78$, $p = .446$), or between verbs with a greater number of thematic options (*break*-verbs) and verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 2.08$, $p = .052$), or between verbs with a greater number of number-of-argument options (*sing*-verbs) and verbs with a lower number of number-of-argument options (*complete*-verbs) ($t(19) = .97$, $p = .343$).

*4.2.2. Sentence task*

In the sentence task, the average accuracy was 92.0% (SD 3.3%, range 85.0 – 96.3%) and the average reaction time was 1489 ms (SD 178 ms, range 1067 – 1786 ms). No participants had to be excluded from the analysis due to low performance. Average accuracy and reaction times in experimental conditions are presented in Table 4.2.

*Table 4.2*. Average accuracy and reaction time in the sentence judgment task in Experiment 3, mean (SD).

| | *Complete*-verbs | *Demand*-verbs | *Sing*-verbs | *Break*-verbs | Semantic fillers | Syntactic fillers |
|---|---|---|---|---|---|---|
| Accuracy | 93.8 % (4.2 %) | 93.5 % (2.9 %) | 94.3 % (3.5 %) | 91.8 % (6.1 %) | 89.5 % (9.9 %) | 89.1 % (8.1 %) |
| Reaction time | 1490 ms (184 ms) | 1471 ms (178 ms) | 1426 ms (172 ms) | 1462 ms (174 ms) | 1556 ms (200 ms) | 1530 ms (213 ms) |

The three Bonferroni-corrected planned paired *t*-tests on reaction times revealed there was no difference in reaction times between verbs with a greater number of subcategorization options (*demand*-verbs) and verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = 1.12$, $p = .277$); verbs with a greater number of thematic options (*break*-verbs) showed slower reaction times than verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 3.30$, $p = .004$); verbs with a greater number of number-of-argument options (*sing*-verbs) showed faster reaction times than verbs with a lower number of number-of-argument options (*complete*-verbs) ($t(19) = 3.57$, $p = .002$).

The three Bonferroni-corrected planned paired *t*-tests on accuracy revealed that there was no difference in accuracy between verbs with a greater number of subcategorization options (*demand*-verbs) and verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = .16$, $p = .878$), or between verbs with a greater number of thematic options (*break*-verbs) and verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 1.76$, $p = .094$), or between verbs with a greater number of number-of-argument options (*sing*-verbs) and verbs with a lower number of number-of-argument options (*complete*-verbs) ($t(19) = .41$, $p = .689$). The results of both tasks in Experiment 3 are summarized in Table 4.3.

*Table 4.3*. Summary of results of Experiment 3.

| Parameter (comparison) | Lexical decision, reaction times | Lexical decision, accuracy | Sentence judgment, reaction times | Sentence judgment, accuracy |
|---|---|---|---|---|
| Number of subcategorization options | * *complete*-verbs > *demand*-verbs | n/s | *n/s* | n/s |
| Number of thematic options | * *sing*-verbs > *break*-verbs | n/s | * *break*-verbs > *sing*-verbs | n/s |
| Number of number-of-argument options | n/s | n/s | * *complete*-verbs > *sing*-verbs | n/s |

* indicates statistically significant effects ($p < .05$). For reaction times analysis, > indicates slower reaction times; for accuracy analysis, > indicates higher accuracy.

**4.3. Discussion**

Experiment 3 aimed to investigate whether the verb's number of subcategorization options, overall number of thematic options and overall number of number-of-argument options affect processing speed and accuracy of healthy speakers at the single-word and sentence level processing. It aimed to provide data for the sentence-level task, since data on processing speed were not collected in Experiment 1, and to replicate the findings for the single-word-level task in Experiment 2. The validity of the experiment is confirmed by high performance on the tasks (high accuracy, as well as reaction times within an expected range), which was expected from healthy participants. Additionally, the validity of the lexical decision task is further confirmed by the fact that the results of Experiments 2 and 3 were very similar: the average lexical decision times for verb groups formed the same hierarchy (*demand*-verbs > *break*-verbs > *complete*-

verbs > *sing*-verbs, where > indicates faster average reaction time), even though the significance of paired comparisons was not the same (see below). Table 4.4 summarizes how behavioral results from Experiment 2 compare to behavioral results from the lexical decision task in Experiment 3.

*Table 4.4*. Comparison of behavioral results in the lexical decision task in Experiments 2 and 3.

| Parameter (comparison) | Experiment 3, reaction times | Experiment 2, reaction times | Experiment 3, accuracy | Experiment 2, accuracy |
|---|---|---|---|---|
| Number of subcategorization options | * *complete*-verbs > *demand*-verbs | * *complete*-verbs > *demand*-verbs | n/s | n/s |
| Number of thematic options | * *sing*-verbs > *break*-verbs | n/s | n/s | * *sing*-verbs < *break*-verbs |
| Number of number-of-argument options | n/s | n/s | n/s | * *sing*-verbs < *complete*-verbs |

* indicates statistically significant effects ($p < .05$). For reaction times analysis, > indicates slower reaction times; for accuracy analysis, > indicates higher accuracy.

*4.3.1. Number of subcategorization options*

In the sentence processing task, the number of subcategorization options did not show a significant effect on either processing speed or accuracy. This result fails to support the hypothesis: it was hypothesized that verbs with a greater number of subcategorization options would be processed slower than verbs with a smaller number of subcategorization options, since the former are more "complex" in terms of quantity of information that needs to be accessed and were associated with greater neural activation in Experiment 1. The result is also inconsistent with most previous studies, which did find a detrimental effect of a greater number of subcategorization options in sentence processing (Fodor, Garrett and Bever, 1968; Holmes & Forster, 1972; Chodorow, 1979), although one previous study failed to find such effect, consistent with our findings (Shapiro, Zurif & Grimshaw, 1987). The finding is basically a null result that may be due to Type II error; thus, it is not possible to make a definite conclusion that the number of subcategorization options does not have any behavioral effects in sentence-level processing.

On the other hand, in the lexical decision task, a greater number of subcategorization options was associated with a faster processing speed, while accuracy was unaffected. This replicated the behavioral findings of Experiment 2, indicating that the result is robust. Although this finding is inconsistent with results of the only previous single-word-level study of the number of subcategorization options that we are aware of (Rodriguez-Ferreiro et al., 2014), which found no significant differences between the two verb categories, it is consistent with our account of results of the neuroimaging Experiment 2. Verbs with a greater number of subcategorization options appear to present less difficulty in single-word processing than verbs with a lower number of subcategorization options because a greater number of subcategorization options may actually "strengthen" verb representations and make them more "robust" by means of building more connections in the mental lexicon (see more detailed discussion in Section 3.4). This may actually facilitate lexical access under processing conditions such as in the single-word-level context, when not all of associated information needs to be fully activated. Lack of effect in a sentence-level task may be caused by competition/mutual neutralization between, on the one hand, the lexical-access advantage of verbs with a greater number of subcategorization options and, on the other hand, a greater computational complexity associated with their integration in a sentence structure.

*4.3.2. Number of thematic options*

To the best of our knowledge, behavioral effects of the number of thematic options have not yet been investigated independently of other VAS characteristics. Our experiment found that this factor elicited opposite effects in single-word level and sentence level processing. At the sentence level, a greater number of thematic options was associated with slower processing speed. This is consistent with our initial hypothesis, namely that verbs with a greater number of thematic options would be more challenging to process in a sentence-level processing task. However, the question remains as to whether this increased difficulty reflects increased demands during retrieval of all of the verb's thematic options or during selection of an appropriate thematic option when integrating the verb into sentence. As discussed above in Section 2.3, the results of ROI analysis of Experiment 1 do not provide a conclusive answer either.

In the single-word-level task, a greater number of thematic options was associated with faster processing speed. The effect is not very robust, since it was not an exact replication of behavioral effects from Experiment 2: in Experiment 2, the effect of the number of thematic options on reaction times was not significant (although the ranking of mean reaction times was the same), whereas the effect on accuracy reached significance (a greater number of subcategorization options was associated with higher accuracy). Nonetheless, the overall pattern indicates that a greater number of thematic options had a facilitatory effect in single-word level processing. This is consistent with our account above about a greater number of VAS options (in this case, thematic options) actually “strengthening” verb representations and making them more “robust” by means of building more connections in the mental lexicon. This may facilitate lexical access under processing conditions such as in the single-word-level context, when not all of associated information needs to be fully activated.

*4.3.3. Number of number-of-argument options*

Finally, the number of number-of-argument options also produced different results depending on the task. In the sentence-level task, a greater number of number-of-argument options had a facilitatory effect on processing speed, while accuracy remained unaffected. This is inconsistent with our initial hypothesis about a greater number of number-of-argument options making verb processing more challenging, as well as with previous studies which did indeed find such detrimental effects (Shapiro, 1987; Shapiro et al., 1989; Ahrens & Swinney, 1995). This was the only instance where a behaviorally facilitatory effect of a greater number of VAS options was found in sentence-level processing. It remains possible that a greater number of VAS options (in this case, number-of-argument options) actually “strengthens” verb representations and makes them more “robust” by means of building more connections in the mental lexicon. However, in order to explain why this facilitatory effect is not neutralized by more challenging sentence-level processing of verbs with a greater number of VAS options (as in the case of subcategorization options and thematic options), one needs to make additional assumptions: either that not all number-of-argument options are fully retrieved in sentence processing and/or that they do not impose an additional load on verb integration into sentence structure. An alternative account of the positive effect of a greater number of number-of-argument options in sentence processing is that this characteristic may reflect how restricted the syntactic use of the verb is. A greater number of number-of-argument options places fewer restrictions on the syntactic structure, making verb use more "lenient", and thus may place a smaller computational load in sentence processing. The present study does not adjudicate between these possible accounts.

In the single-word-level task (for which, to the best of our knowledge, there are no data for comparison from the previous literature), the number of number-of-argument options did not have any significant effects on the processing speed or accuracy. However, this is a null result and thus should be interpreted with caution. Moreover, the null result is inconsistent with the behavioral findings of Experiment 2. Experiment 2 did not find an effect on reaction times either (the ranking of mean reaction times per condition was the same as in Experiment 3) but found that a greater number of number-of-argument options was associated with significantly lower accuracy (the ranking of mean accuracy per condition was the same as in Experiment 3). Thus, the findings of Experiment 3 with regard to the behavioral effect of the number of number-of-argument options are not robust enough in order to interpret whether they are consistent with our initial hypothesis that accessing a greater number of number-of-argument options would be associated with a greater processing cost in single-word processing.

#### *4.3.4. Summary*

To summarize, Experiment 3 found that effects of all three investigated VAS characteristics were modulated greatly by the task. The results for the number of subcategorization options and the number of thematic options were similar: both factors demonstrated a facilitatory effect of greater VAS complexity in the single-word-level task; in the sentence-level task, a greater number of thematic options demonstrated a detrimental effect, whereas the number of subcategorization options had no effect. These results support our account of neuroimaging Experiments 1 and 2. Specifically, they suggest that a greater number of VAS options may in fact “strengthen” verb representations and make them more “robust” by means of building more connections in the mental lexicon. This may actually facilitate lexical access under processing conditions such as in the single-word-level context, when not all of the associated information needs to be fully activated, whereas in conditions where all information needs to be fully activated, selected and/or integrated into larger units such as sentences, a greater number of options has a detrimental effect. The behavioral results support the interpretation of a greater neural activation as a sign of a greater processing load, and do not provide any evidence in favor of a less traditional interpretation of greater neural activation as a sign of more robust and temporally focused processing, leading to temporally uniform and easier detectable activation. If this were the case, better behavioral performance would be observed for conditions associated with greater neural activation.

However, the above pattern did not hold for the third investigated characteristic, the number of number-of-argument options, where a greater complexity had a positive (rather than negative, as initially hypothesized) effect in sentence processing and no to very weak negative effect in single-word processing. The positive effect in sentence processing may speculatively be explained by a greater number of number-of-argument options placing fewer restrictions on the syntactic structure, making verb use in sentences more “lenient”, and thus placing a smaller computational load in sentence processing. Still, taken together, the lack of robustness of behavioral and neural effects of the number of number-of-argument options, as well as the inconsistency between behavioral and neuroimaging findings suggest that the number of number-of-argument options may not be a VAS characteristic that is stored as part of lexical entry of the verb and exhaustively accessed in verb processing.

One should also make a cautionary note that participants were college-aged individuals with no history of language disorders and thus performed “at ceiling” on the tasks. Thus, lack of effects of any investigated parameters on accuracy needs to be interpreted with caution, since these may be due to Type II error (i.e., the study failing to detect a significant effect that is present in the population).

# CHAPTER 5

## GENERAL DISCUSSION

The three experiments presented in this dissertation investigated whether other VAS characteristics besides the well-studied parameter of the number of arguments (namely, the number of subcategorization options, the number of thematic options and the number of number-of-argument options) modulate the behavioral processing cost and neural correlates of verb processing in two different processing conditions: single-word processing and sentence processing.

### 5.1. Task-dependent effects of VAS characteristics

The overall results indicate that these less studied VAS characteristics are also stored in association with the lexical entry of the verb[10] and are accessed even when not directly triggered by context, modulating neural correlates and/or behavioral cost of verb processing. However, the most important finding of the present research is that such effects are task-dependent. It is not always the case that the processing load is greater for verbs with representations containing more complex VAS options (i.e., a greater amount of linguistic information) – rather, it depends on the task whether greater VAS complexity will actually increase or reduce the processing cost. Such task-dependent

[10] Similarly to previous sections (see Footnote 2), this section uses the term "lexical entry" as a traditional way to describe all information about the word that is available to the language user (e.g., Levelt, 1992), without any assumptions about the nature of this lexical knowledge, which may be stored in a distributed way by means of connections between elements (e.g., Elman, 2011) rather than in separate "lexical entry" units.

effects have been noted in many fields of psycholinguistic research: among them are, to name just a few, task-dependent effects of phonotactic probability and phonological neighborhood density on lexical access as measured by ERPs (Vitevitch & Luce, 1999), varied effects of lexical frequency in different reading tasks (Fischer-Baum et al., 2014), inconsistent performance across syntactic (sentence comprehension) tasks in aphasia (DeDe & Caplan, 2006). Task-dependent effects arise because the goal of processing modulates which subprocesses are brought out and which linguistic features need to be accessed, and how deeply or shallowly, for the purposes of performing the task; this shift of focus in processing may be adopted strategically (consciously) or occur in an automated way (Vitevitch & Luce, 1999; Fischer-Baum et al., 2014). However, task-dependency has not received much attention in VAS literature yet.

The pattern of task-dependency in the present research was similar for the number of subcategorization options and the number of thematic options. For both characteristics, a greater VAS complexity (i.e., a greater number of VAS options) played a facilitatory role in the single-word-level task (as reflected by faster/more accurate behavioral performance and/or less extensive neural recruitment) and a negative role in sentence-level processing task (as reflected by poorer behavioral performance and/or more extensive neural recruitment). To account for this, one can suggest that a greater number of VAS options may in fact “strengthen” verb representations and make them more “robust” or provide them with additional access routes by means of building more connections in the mental lexicon (similar to effects of semantic neighborhood density, e.g., Buchanan, Westbury & Burgess, 2001; Shaoul & Westbury, 2010). This may actually facilitate lexical access under processing conditions such as in the single-word-level context, when not all of associated information needs to be fully activated, whereas representations of verbs with a lower number of VAS options may lack these beneficial connections and thus be more difficult to access. On the other hand, sentence processing requires not only accessing VAS information but also selecting and integrating appropriate components of this information. Under these conditions, the beneficial effect of more robust representations of verbs with a greater number of VAS options may be neutralized or overridden by a greater load associated with inhibiting irrelevant options, selecting appropriate options and integrating them into context.

Our neuroimaging results suggest that the specific nature of this additional load in sentence processing may be different for the number of subcategorization options and the number of thematic options. A greater number of subcategorization options was associated with activation in left posterior temporal and temporo-parietal areas in sentence processing. These areas have been associated with semantic storage/retrieval (e.g., Binder et al., 2009). Thus, one may speculate that processing of sentences containing verbs with a greater number of subcategorization options poses greater demands on fully retrieving possible options, possibly in prediction/anticipation of the upcoming sentence material (Kamide et al., 2008). A greater number of thematic options was associated with activation in white matter underlying left frontal regions. This area was not included in our a priori defined list of regions of interest and it is thus not possible to induce the specific nature of the additional processing load. However, since activation was close to pars orbitalis and opercularis of the left inferior frontal gyrus and was likely overlapping with fiber tracts that feed these regions, which are often associated with structure building and integration (e.g., Meyer et al., 2012; Thompson & Meltzer-

Asscher, 2014), it is still possible to speculate that the processing of sentences with verbs with a greater number of thematic options may pose greater demands on selecting an appropriate VAS option and/or integrating it into the sentence.

The above pattern, with a greater VAS complexity having a facilitatory effect in single-word processing (unlike sentence processing) is inconsistent with most previous literature, which has widely used single-word-level tasks and has largely agreed that a greater VAS complexity corresponds to a greater processing cost. However, there are occasional reports of facilitatory effects of greater VAS complexity, as in the present study. For example, Thompson et al. (2007) also report faster processing of verbs with a greater number of arguments in a lexical decision experiment. One should also note that most previous VAS research has focused on the number of arguments. Literature on other VAS characteristics is more sparse and lacks consistency, possibly due to differences in specific stimuli and, importantly, experimental design: i.e., which verb groups are compared in order to induce effects of specific VAS characteristics. For example, in order to draw conclusions on the effects of the number of number-of-argument options, Metlzer-Asscher et al. (2015) compared alternating (one/two-argument) verbs to both one-argument and two-argument non-alternating verbs, whereas in the present research the latter group was restricted to two-argument non-alternating verbs; Shetreet et al. (2007) employed a parametric design to analyze the effect of the number of subcategorization options, whereas the present research made a binary comparison of verbs with one versus multiple subcategorization options; etc. The present research adds to this body of literature and will hopefully contribute to future understanding of the factors accounting for inconsistencies. The way to achieve this understanding may be to systematically investigate VAS effects across tasks (both at the single word level, on a continuum from more "superficial" tasks such as lexical decision to picture-based and video-based action naming (den Ouden et al., 2009), and at the sentence level), as well as across linguistic contexts (e.g., the effect of the number of thematic options should be investigated in intransitive contexts, in transitive contexts and when no context is available, similar to the approach taken by Shetreet et al. (2010)).

Overall, our results suggest that there may be several levels of verb processing, with varied nature of VAS access, depending on the task. At the single-word level, verbs do not have to be actively processed and there is therefore no need to access their VAS options. Still, VAS characteristics have an impact in that more linguistically complex verbs may benefit from multiple lexical access routes that have been established in the mental lexicon. The second level is verb processing in sentence comprehension. For the purposes of efficient processing (e.g., for prediction of upcoming sentence structure), potential VAS options of the verb are retrieved from the mental lexicon, which leads to greater storage/retrieval demands for more complex verbs, reversing the direction of VAS effects compared to the first processing level. One may hypothesize that there also exists a third level of verb processing that was beyond the scope of the present research. It would be the level of processing verbs in an active sentence-level task such as sentence production. One may hypothesize that at this level, VAS options would need to not only be retrieved, as in sentence-level comprehension, but also to be actively manipulated for the purposes of structure-building and integration in a sentence. This hypothesis could be tested by neuroimaging research using a sentence-level production task and would be supported by increased activation of brain areas associated with structure-building/integration for verbs of greater VAS complexity. In terms of behavioral performance, which could also be investigated in future research, more complex VAS is hypothesized to have a detrimental effect at the level of sentence-level production, similar to effects in sentence-level comprehension.

### 5.2. Semantic account of VAS effects

All the aforesaid only pertains to the number of subcategorization options and the number of thematic options. The third investigated VAS characteristic, the number of number-of-argument options, did not yield a similar pattern of results. In the sentence-level task, a greater number of number-of-argument options had a facilitatory effect at the behavioral level and showed no additional neural recruitment, whereas in the single-word-level task, a greater number of number-of-argument options showed no to very weak detrimental effect, with areas of additional activation for verbs with both a greater and a smaller number of number-of-argument options. However, the results do not appear very robust, as indicated by small volumes of brain activation clusters, none of which survived an FWE correction for multiple comparisons, and by lack of replication of behavioral results between Experiments 2 and 3. Moreover, the findings on the number of number-of-argument options are not very robust in previous literature either, with most studies failing to find a significant effect of this VAS characteristic (Ahrens & Swinney, 1995; Shetreet et al., 2010; Meltzer-Asscher et al., 2015).

In an attempt to explain why the number of number-of-argument options yielded results different from other VAS characteristics, one may point out that it may be the most “syntactic” out of the investigated VAS characteristics. In other words, the other two investigated VAS characteristics may be associated with particular properties of the verbs' meanings. For instance, verbs with a greater number of subcategorization options have in common the fact that their semantics allows complementation by a proposition (a vast theoretical linguistic literature discusses semantic properties of such verbs: e.g., Rudanko, 1996); for verbs with a greater number of thematic options, the common semantic property is that they typically describe a change of state (Wright, 2002; Chierchia, 2003). Even though experimental groups were matched for imageability as a crucial semantic parameter, these inherent differences in semantics still remain. There do not seem to be such salient semantic differences between verbs with a greater versus lower number of number-of-argument options.

Based on the fact that effects are found primarily for VAS characteristics intertwined with semantic properties, one may speculate that the neural effects of the number of subcategorization options and thematic options may actually be mediated by accessing and selecting/integrating *semantic* information associated with these verbs, rather than a separate grammatical component of their lexical entries that contains VAS information. This speculation finds support in the fact that greater activation for verbs with a greater number of subcategorization/thematic options was observed in the sentence-level task, which requires deep semantic processing, but not in the lexical decision that only requires superficial access to lexical knowledge about the verb. Thus, taken together, our findings may indicate that an additional load in the processing of verbs with a greater number of subcategorization and thematic options is largely mediated by inherent semantic properties of such verbs, rather than by automated exhaustive access to purely grammatical VAS information. In terms of lexicalist versus constructivist accounts, this account would be most supportive of constructivism, which argues that there is no need for a separate VAS module in lexical representations of verbs. The semantic account may also pertain to robust effects of the number of arguments (not investigated here) found in previous literature. The number of arguments is a highly semantically meaningful characteristic that reflects the number of participants in the event denoted by the verb. Thus, any effects of the number of arguments may be due to semantic/conceptual processing of participant roles, rather than to processing of representations that have grammatical nature.

Another finding from the previous literature that appears consistent with the semantic account is that VAS effects in people with non-fluent/agrammatic aphasia are similar to those found in healthy speakers: e.g., individuals with aphasia also demonstrate a detrimental effect of a greater number of arguments (Kim & Thompson, 2000; Collina et al., 2001; Thompson et al., 1997, 2003). So far, researchers have mainly taken this evidence to argue that VAS *representations* are intact in aphasia, whereas VAS *processing* is impaired (e.g., Kielar et al., 2012). The present research suggests another account: VAS effects in aphasia similar to those in healthy individuals may actually be due to near-normal semantic processing that mediates VAS effects, rather than to intactness of syntactic representations. In line with this, some evidence indicates that individuals with Wernicke's aphasia do not demonstrate the same VAS effects as healthy individuals: e.g., they show no online sensitivity to thematic properties of verbs presented in sentences (Shapiro, Gordon, Hack & Killackey, 1993; Russo, Peach & Shapiro, 1998) (although see (Edwards & Bastiaanse, 1998) for normal-like distribution of VAS characteristics in spontaneous speech of individuals with fluent aphasia). Since syntactic representations are not expected to be impaired in Wernicke's aphasia, evidence of absence of typical VAS effects in this population provides additional support for the idea that VAS effects may be mediated by the verbs' semantics rather than by a separate grammatical component of their representations. Whitworth et al. (2015) report a case of a patient who does not have any lexical-semantic deficits in single-word verb and noun production but cannot produce correct VAS structures. We argue that although this dissociation provides important information for selection of language treatment or testing tasks, it does not necessarily disprove the 'semantic' account of VAS effects, since the ability to use semantic information to guide sentence construction likely relies on different mechanisms than retrieval of phonological forms based on semantic information, as in naming.

Further research can be conducted to test the 'semantic' account of VAS effects. This account could potentially be tested in an experiment that would separately manipulate respective VAS and semantic characteristics of verbs. However, these properties may be inherently interwoven too much, making it impossible to generate a sufficient number of stimuli. Another way to probe the account may be to use identical experimental stimuli in two tasks which would both use the same level of processing units (e.g., single words, verb-noun combinations or sentences) but differ on how much deep semantic processing they require. One of the tasks (e.g., single-word semantic judgment) would draw more heavily on semantic processing, while the other one would be more superficial (e.g., single-word lexical decision). If such experiment would find that VAS-associated activation is greater in a task that places greater demands on semantic processing, this could imply that it likely reflects semantic processes and thus that the nature of VAS effects is semantic, rather than grammatical.

Arguing that effects of VAS parameters may possibly be of semantic nature does not imply that verbs should not be characterized in terms of VAS parameters or that those should not be taken into account when characterizing verb complexity. Even though VAS effects may in fact be mediated by semantic properties of verbs, rather than necessarily imply the presence of a separate VAS component in the lexical entry of the verb, VAS parameters may still be an appropriate framework for quantifying such semantic properties, which may otherwise be too subtle to measure and report. In other words, VAS parameters can be a suitable tool for measuring and testing semantic complexity of verbs.

### 5.3. Implications for aphasia research and treatment

Regardless of the possibly semantic nature of VAS effects, it may still be beneficial to take them into account when selecting verb stimuli for complexity-based aphasia treatments. So far, such treatments have mainly been based on characterizing verbs on the number of arguments (Bazzini et al., 2012; Thompson et al., 2013), sequencing them in the order from verbs with less arguments to verbs with more arguments (Rochon et al., 2005) or the other way around (Thompson et al., 2013), depending on the approach to practice and generalization. The present research indicates that other VAS characteristics (the number of subcategorization options and the number of thematic options) also affect the cost of verb processing. Thus, sequencing of stimuli in complexity-based treatments may potentially be improved by incorporating these two characteristics when assigning verbs to groups of differing complexity. The third investigated VAS characteristic, the number of number-of-argument options, shows very inconsistent effects at the behavioral and neural level both in the present research and in previous literature. Thus, its manipulation would seem less relevant in language treatments based on VAS complexity, unless new research provides evidence of a robust effect of the number of number-of-argument options in aphasia. Another clinical implication for behavioral aphasia treatments is that since VAS effects may have a semantic nature, activities aiming to improve VAS processing may be the most beneficial if they strongly focus on the meanings of verbs and their arguments (as in, e.g., Verb Network Strengthening Treatment, (Edmonds, Nadeau & Kiran, 2009; Kwag et al., 2014)), rather than on grammatical transformations or on automated access to verb forms.

Finally, another clinical area for which the present research could have practical implications are brain stimulation language treatments and, to a certain extent, protocols of intraoperative language mapping, for which verb tasks have been recently suggested to be more promising than noun tasks (Havas et al., 2015). So far, brain stimulation paradigms that have attempted to modulate verb processing have mainly targeted the left temporo-parietal junction (Malyutina & den Ouden, submitted) and left inferior frontal regions (Cappa et al., 2002; Fertonani et al., 2008; Marangolo et al., 2013). In the present study, brain areas activated in association with different VAS characteristics were very diverse, including bilateral (although mainly left-lateralized) frontal, temporal and parietal areas. In other words, there was no single area associated with VAS processing in general: rather, processing of different dimensions of VAS information under different conditions relies on different brain circuits. However, the general brain area that appears to be frequently activated across contrasts but has not received much attention in previous research was the left middle temporal gyrus. Its posterior portion showed increased activation for a greater number of subcategorization options in sentence-level processing and a lower number of thematic options in single-word-level processing; its mid-anterior area showed increased activation for a lower number of thematic options in single-word-level processing and, although that appears to be a less reliable finding, for a lower number of number-of-argument options in single-word-level processing.. The activation of left middle temporal gyrus has also been observed in previous research (posterior portion activated for the number of arguments (den Ouden et al., 2009), mid-anterior and posterior portions activated for the number of subcategorization options (Shetreet et al., 2010)). Thus, it appears that the left middle temporal gyrus may also be an important area involved in verb processing and could potentially serve as a target for brain stimulation treatments targeting verb processing.

In order to develop and improve language treatments targeting verb processing, it is important to rely not only on studies that provide foundational data on normal verb processing in control participants, but also on studies in people with language disorders, despite the challenges due to the diversity of this population. Thus, further research is needed that would directly address how the three investigated VAS characteristics affect verb processing in aphasia and whether they have the same facilitatory or detrimental effects as in healthy participants. Pilot work in our lab (briefly presented in Section 1.3) suggests that the distribution of verbs with various numbers of subcategorization options may be the same in spontaneous speech in individuals with aphasia and in healthy speakers. More research is needed on whether the effect of the number of subcategorization options will also be qualitatively the same in individuals with aphasia and in healthy speakers in confrontation tasks, as well as whether the effects of the number of thematic options will be identical to those found in healthy speakers. Based on the tentatively semantic nature of the effects, one may hypothesize that they will indeed be similar (at least in non-fluent agrammatic aphasia, with preserved lexical-semantic processing), but further research is needed to test this hypothesis.

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# APPENDIX A – FULL LIST OF STIMULI FROM THE LEXICAL DECISION TASK (EXPERIMENTS 2 AND 3)

*Table A.1.* Full list of *complete*-verbs used.

| # | Verb |
|---|---|
| 1 | abandon |
| 2 | complete |
| 3 | consume |
| 4 | create |
| 5 | destroy |
| 6 | encounter |
| 7 | fulfill |
| 8 | own |
| 9 | produce |
| 10 | accomplish |
| 11 | contact |
| 12 | invent |
| 13 | acquire |
| 14 | conquer |
| 15 | ruin |
| 16 | capture |
| 17 | wreck |
| 18 | discard |
| 19 | generate |
| 20 | whisk |

*Table A.2.* Full list of *break*-verbs used.

| # | Verb | Example of transitive use | Example of intransitive use |
|---|---|---|---|
| 1 | open | The janitor opened the door. | The door opened. |
| 2 | break | The worker broke the handle. | The handle broke. |
| 3 | operate | The worker operated the machine. | The service operated on weekdays. |
| 4 | accelerate | The driver accelerated the vehicle. | The vehicle accelerated. |
| 5 | spin | The child spun the top. | The dancer spun gracefully. |

| | | | |
|---|---|---|---|
| 6 | broaden | The book broadened my horizons. | My horizons broadened. |
| 7 | dry | The mother dried the laundry. | The laundry dried in the sun. |
| 8 | gather | The janitor gathered trash. | The staff gathered for a meeting. |
| 9 | unite | The law united the state. | The state united after the war. |
| 10 | assemble | The girl assembled the desk. | The crowd assembled in the hall. |
| 11 | close | The teacher closed the door. | The door closed. |
| 12 | accumulate | The lady accumulated a fortune. | Money accumulated in her account. |
| 13 | worsen | The crisis worsened the situation. | The patient's condition worsened. |
| 14 | collapse | The wind collapsed the barn. | The barn collapsed. |
| 15 | burn | The burglar burnt the house. | The candle burnt in the dark. |
| 16 | dissolve | The researcher dissolved the chemical. | The chemical dissolved fast. |
| 17 | brighten | The sun brightened the day. | The sky brightened. |
| 18 | drop | The customer dropped the bags. | The temperature dropped. |
| 19 | grow | The gardener grew flowers. | The child grew fast. |
| 20 | collect | The girl collected stamps. | The public collected in the hall. |

To justify inclusion into this group, examples of transitive and intransitive use (with different thematic roles of the sentence subject) are provided.

*Table A.3*. Full list of *sing*-verbs used.

| # | Verb | Example of transitive use | Example of intransitive use |
|---|---|---|---|
| 1 | draw | The girl drew a picture. | The girl drew in her free time. |
| 2 | visit | Her parents visited her often. | Her parents visited last week. |
| 3 | knit | The grandmother knitted a sweater. | The grandmother knitted in her free time. |
| 4 | perform | Her sister performed a song. | Her sister performed on stage. |
| 5 | sing | Mary sang a song. | Mary sang well. |
| 6 | divorce | The doctor divorced his wife. | The doctor divorced two years ago. |
| 7 | marry | John married a co-worker. | John married young. |
| 8 | miss | The boy missed the target. | The sniper missed pathetically. |
| 9 | obey | The soldier obeyed the order. | The soldier silently obeyed. |
| 10 | clean | Adam cleaned the kitchen. | Adam cleaned all Sunday. |
| 11 | achieve | The girl achieved the goal. | The girl achieved well in school. |
| 12 | recite | The child recited a poem. | The child recited loudly. |
| 13 | embroider | Anna embroidered the pillow. | Anna embroidered in her spare time. |
| 14 | adopt | The couple adopted a baby. | The couple adopted in 2002. |
| 15 | hum | The driver hummed a song. | The driver hummed softly. |
| 16 | rehearse | The cast rehearsed the play. | The cast rehearsed for two hours. |
| 17 | follow | The soldier followed the leader. | The car followed closely behind me. |
| 18 | entertain | My aunt entertained the guests. | Sarah was not good at entertaining. |
| 19 | exaggerate | My mother exaggerated the problem. | My mother exaggerated in her letter. |
| 20 | advertise | The company advertised the product. | The company advertised on TV. |

To justify inclusion into this group, examples of transitive and intransitive use (with the same thematic roles of the sentence subject) are provided.

*Table A.4.* Full list of *demand*-verbs used.

| # | Verb | Example of use complemented by a noun phrase | Example of use complemented by a phrase of different category |
|---|---|---|---|
| 1 | hate | The girl hated dogs. | The girl hated that her parents were away. |
| 2 | demand | The attorney demanded the truth. | The attorney demanded that they listen to him. |
| 3 | reveal | The test revealed the true cause. | The test revealed that the disease was caused by a virus. |
| 4 | promise | The president promised new tax cuts. | The president promised that there will be new tax cuts. |
| 5 | arrange | The businessman arranged a meeting. | The businessman arranged that they meet. |
| 6 | declare | The state declared independence. | The convict declared that he had been unaware of the penalty. |
| 7 | neglect | The woman neglected her children. | The worker neglected to perform her duties. |
| 8 | announce | The model announced the divorce. | The model announced that they were divorcing. |
| 9 | advise | The doctor advised a new medication. | The doctor advised that the patient should take a new medication. |
| 10 | witness | The neighbor witnessed the crime. | The neighbor witnessed in court. |
| 11 | challenge | The book challenged her views. | Mr. Jones challenged that he could remain the executive director. |
| 12 | predict | The old man predicted the end of the world. | The old man predicted that this would be the end. |
| 13 | desire | The public desired a change. | The public desired that everything should change. |
| 14 | adore | John adored his wife. | Mary adored when he called. |
| 15 | conceal | The employee concealed the truth. | The employee concealed that he had been accused of the crime. |
| 16 | discover | The traveler discovered a new land. | The host discovered that the guests had left. |
| 17 | discuss | The panel discussed the law. | The panel discussed how the law should be interpreted. |
| 18 | accept | The family accepted the loss. | The brother accepted that it was reasonable. |
| 19 | rule | The king ruled the country. | The king ruled that it should be considered illegal. |
| 20 | seek | The client sought the truth. | The player sought to win. |

To justify inclusion into this group, examples of use complemented by a noun phrase and by a phrase of a different category (e. g., subordinate clause) are provided.

# APPENDIX B – FULL LIST OF STIMULI FROM THE SENTENCE JUDGEMENT TASK (EXPERIMENTS 1 AND 3)

*Table B.1.* Full list of stimuli with *complete*-verbs used in the sentence judgement task.

| # | Verb | Sentence 1 | Sentence 2 |
|---|---|---|---|
| 1 | abandon | The army abandoned the city. | The collie abandoned her puppy. |
| 2 | complete | The user completed the survey. | The students completed the exam. |
| 3 | consume | The society consumed the resources. | The engine consumed the fuel. |
| 4 | create | The artist created a masterpiece. | The law created the problem. |
| 5 | destroy | The hurricane destroyed the roofs. | The storms destroyed the houses. |
| 6 | encounter | The expedition encountered the tribes. | The police encountered the fight. |
| 7 | fulfill | The governor fulfilled the promise. | The teenager fulfilled her dreams. |
| 8 | own | The farmer owned the terrain. | The grandfather owned the apartment. |
| 9 | produce | The factory produced the device. | The band produced the album. |
| 10 | accomplish | The team accomplished the mission. | The teacher accomplished the goal. |
| 11 | contact | The client contacted the clerk. | The principal contacted the parents. |
| 12 | invent | The engineer invented the machine. | The insurer invented the scheme. |
| 13 | acquire | The apprentice acquired the skills. | The millionaire acquired the properties. |
| 14 | conquer | The tribes conquered the land. | The army conquered the nation. |
| 15 | ruin | The tornado ruined the mansion. | The heat ruined the salad. |
| 16 | capture | The hunter captured the tiger. | The cat captured the mouse. |
| 17 | wreck | The captain wrecked the ship. | The rocks wrecked the ship. |
| 18 | discard | The clerk discarded the trash. | The baby discarded his blanket. |
| 19 | generate | The factory generated the power. | The assembly generated much dissent. |
| 20 | whisk | The cook whisked the eggs. | The wife whisked the mixture. |

*Table B.2.* Full list of stimuli with *break*-verbs used in the sentence judgement task.

| # | Verb | Sentence 1 | Sentence 2 |
|---|---|---|---|
| 1 | open | The janitor opened the door. | The woman opened the box. |
| 2 | break | The thief broke a lock. | The worker broke the glass. |
| 3 | operate | The worker operated the crane. | The driver operated the lift. |
| 4 | accelerate | The pilot accelerated the helicopter. | The group accelerated their departure. |
| 5 | spin | The toddler spun the top. | The athlete spun the ball. |
| 6 | broaden | The workers broadened the street. | The students broadened their knowledge. |
| 7 | dry | The model dried her hair. | The swimmer dried the towel. |
| 8 | gather | The mayor gathered the citizens. | The organizers gathered the protesters. |

| | | | |
|---|---|---|---|
| 9 | unite | The campaign united the politicians. | The leader united the factions. |
| 10 | assemble | The king assembled his subjects. | The principal assembled the students. |
| 11 | close | The owner closed the store. | The worker closed the valve. |
| 12 | accumulate | The carpet accumulated the dirt. | The collector accumulated the stamps. |
| 13 | worsen | The rain worsened the situation. | The policies worsened the crisis. |
| 14 | collapse | The explosion collapsed the warehouse. | The blast collapsed the building. |
| 15 | burn | The writer burned the manuscript. | The housewife burnt the pan. |
| 16 | dissolve | The chemist dissolved the compound. | The water dissolved the sugar. |
| 17 | brighten | The sun brightened the sky. | The lamp brightened the hall. |
| 18 | drop | The cashier dropped the receipt. | The mover dropped the box. |
| 19 | grow | The gardener grew the vegetables. | The farmer grew the cotton. |
| 20 | collect | The scientist collected the samples. | The researcher collected the insects. |

*Table B.3.* Full list of stimuli with *sing*-verbs used in the sentence judgement task.

| # | Verb | Sentence 1 | Sentence 2 |
|---|---|---|---|
| 1 | draw | The architect drew the temple. | The artist drew a helicopter. |
| 2 | visit | The student visited the gallery. | The family visited the coast. |
| 3 | knit | The grandmother knitted the pattern. | The lady knitted the sweater. |
| 4 | perform | The musician performed the songs. | The actress performed a monologue. |
| 5 | sing | The child sang a carol. | The choir sang the chorus. |
| 6 | divorce | The journalist divorced his wife. | The actress divorced her husband. |
| 7 | marry | The teacher married her colleague. | The director married his girlfriend. |
| 8 | miss | The player missed the target. | The plane missed the runway. |
| 9 | obey | The suspect obeyed the orders. | The toddler obeyed the command. |
| 10 | clean | The maid cleaned the room. | The janitor cleaned the classrooms. |
| 11 | achieve | The group achieved the result. | The writer achieved great success. |
| 12 | recite | The teacher recited the poem. | The author recited the story. |
| 13 | embroider | The princess embroidered the pillow. | The cousin embroidered the patch. |
| 14 | adopt | The applicants adopted a toddler. | The family adopted a baby. |
| 15 | hum | The runner hummed the melody. | The baby hummed a tune. |
| 16 | rehearse | The actors rehearsed the play. | The cast rehearsed their lines. |
| 17 | follow | The dinner followed the lecture. | The dogs followed the trail. |
| 18 | entertain | The game entertained the guests. | The comedy entertained the audience. |
| 19 | exaggerate | The report exaggerated the details. | The media exaggerated the risks. |
| 20 | advertise | The flyer advertized the performance. | The school advertized the openings. |

*Table B.4.* Full list of stimuli with *demand*-verbs used in the sentence judgement task.

| # | Verb | Sentence 1 | Sentence 2 |
|---|---|---|---|
| 1 | hate | The swimmer hated the referee. | The sister hated the soup. |
| 2 | demand | The buyer demanded a refund. | The landlord demanded the keys. |
| 3 | reveal | The records revealed the secrets. | The test revealed the flaws. |
| 4 | promise | The mayor promised a change. | The union promised a strike. |
| 5 | arrange | The florist arranged the flowers. | The planners arranged the wedding. |
| 6 | declare | The president declared a partnership. | The queen declared her will. |
| 7 | neglect | The boss neglected the proposals. | The babysitter neglected the kids. |
| 8 | announce | The couple announced their engagement. | The radio announced the decision. |
| 9 | advise | The mentor advised a revision. | The judge advised the prisoner. |
| 10 | witness | The neighbor witnessed the attack. | The couple witnessed the sunrise. |
| 11 | challenge | The experiment challenged the theories. | The tasks challenged the class. |
| 12 | predict | The prophet predicted a war. | The forecast predicted the weather. |
| 13 | desire | The society desired a reform. | The client desired a replacement. |
| 14 | adore | The aunt adored the cats. | The sister adored the skirt. |
| 15 | conceal | The guard concealed the weapon. | The maid concealed the envelope. |
| 16 | discover | The traveler discovered the tribe. | The scientists discovered the insect. |
| 17 | discuss | The board discussed the policies. | The speaker discussed the drug. |
| 18 | accept | The winner accepted the prize. | The emperor accepted the gift. |
| 19 | rule | The king ruled the country. | The mayor ruled the city. |
| 20 | seek | The refugee sought the protection. | The freshman sought the scholarship. |